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Fog Dispersion

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LIST OF SYMBOLS

d	Jet diameter
E	Electric field
H	Height of space-charge cloud
H_c	Center boundary height
H_i	Inner boundary height
H_o	Outer boundary height
I	Current due to flow of charged particles
n	Charged particle concentration
n_r	Number of droplets of radius r
q	Charge per particle
Q	Charge strength
r	Radial distance
r_d	Droplet radius
r_j	Jet radius
Re	Reynolds number
U_f	Free stream velocity
U_j	Jet velocity
U'	Mean jet velocity
v	Visibility
w	Liquid water content
x	Height, distance
z	Electric mobility
γ	Potential core length

μ	Viscosity
v	Particle velocity

1.0 INTRODUCTION

A feasibility study of economically viable techniques for dispersing warm fog in support of aviation operations under conditions of severely restricted visibility is reported. Viability was assessed by a review of the literature, personal communications with scientists, and an analysis of the information obtained. The results of the assessment are presented in Sections 2.0 and 3.0. Section 2.0 discusses four techniques for dispersing warm fog: evaporation suppression, downwash mixing, seeding with hygroscopic material, and thermal techniques. Particular emphasis of this study was given to charged particle techniques, and Section 3.0 is devoted to a detailed discussion and analysis of charged particle, warm fog dispersal techniques. A comparison cost based on current estimates of the thermal technique to the electric charged particle technique is also provided in this section. Section 4.0 provides conclusions and recommendations resulting from the study while Section 5.0 lists those references directly referred to in the text. Section 6.0 presents a much more extensive bibliography encompassing literature relevant to the study. Finally, Appendix 1 summarizes in a concise format those references of particular pertinence to the dispersal of fog by electric particle techniques.

Previous studies have indicated that thermal techniques, although effective, are very expensive for routine airport operations, as well as being detrimental to the environment. Techniques such as seeding or helicopter downwash are practical for small-scale or temporary fog clearing but are probably not useful for airport operations on a routine basis. The tudy indicates, however, that charged particle technique concepts have the potential necessary to provide a viable system of dispersing warm fog at airports. To fully assess this potential, however, several questions concerning the physical processes of the technique, the instrumentation required to conduct experimental measurements, the possible interference to aircraft operations, and others must be answered prior to the development and installation of an operational system.

This investigation has identified several important factors which are germane to the overall viability of the charged particle technique. These factors given the most complete discussion herein are charged particle generator characteristics, jet penetration, charge concentration decay in the jet, mechanisms of fog cloud concentration dispersion, and cost estimates.

It is concluded to fully understand charged particle techniques additional theoretical modeling and small-scale field testing are required. Prior to planning the field tests, a careful evaluation of existing instrumentation and of the necessary development of new instrumentation to carry out a meaningful experiment is needed. Also, questions relative to safety, in particular, the potential of corona discharge during aircraft refueling operations, the effects of the electric field on on-board microamp control systems, etc., need to be fully evaluated.

2.0 LITERATURE SURVEY

A review of the literature concerned with warm fog dispersal is presented here to provide an understanding of the basic principles and the experimental and theoretical research which has been conducted to date. A compilation of significant reports given in the appendix illustrates the type of articles surveyed and the information obtained. This compilation is by no means all inclusive but serves to outline some of the significant reports and articles.

2.1 State-of-the-Art Summary

Many techniques to dissipate warm fog are successful when applied to small volumes and/or over short time intervals. However, applying these techniques to an airport runway is often a difficult and costly procedure. Thermal and charged particle techniques show promise in this regard.

An adequate assessment of fog dissipation techniques requires a basic knowledge of fog formation and decay. Although the exact microphysics of fog precipitation, growth, and decay are not completely understood, some of the basic conditions and properties which have been reported are summarized in Table 2-1. It is apparent from this table that the combination of two basic factors appears to control fog formation. These are the concentration and type of nuclei and the concentration and temperature of the water vapor. Therefore, to effect a change in either the incipient or the developing states of a fog, a change in droplet and nucleus population or properties and/or a change in temperature or concentrations of water vapor must occur. To be effective, a fog dispersal system must change at at least one of these basic parameters.

Many methods for prevention and dissipation of fog have been shown to be technically possible. A representative list of the different techniques which offer promise and could possibly justify additional research is given in Table 2-2. These techniques and their relative merits are

TABLE 2-1. SOME REPORTED FOG CONDITIONS AND PROPERTIES

FOG TYPE	RADIATION	ADVECTION
Liquid water content (g m^{-3})	0.10-0.25	0.17-0.70
Vertical thickness: (m)		
typical	0-100	0-200
severe	0-300	0-600
Horizontal visibility (m)	~ 100	80-300
Drop concentration (number cm^{-3})	60-210	20-150
Droplet diameter, mean (μm)	10	20
Droplet diameter, range (μm)	5-35	10-120
Nuclei sizes (μm)	0.08-0.8	0.1-12
Nuclei type	Combustion products	Coastal chlorides and nitrates
Wind speed (m s^{-1})	0.5-4	0.5-20
Temperature (°C)	5-20	5-20

TABLE 2-2. TECHNIQUES WHICH SHOW POTENTIAL FOR IMPROVING VISIBILITY IN WARM FOG

1. Evaporation suppression due to monolayer deposition on the moisture source.
2. Evaporation of droplets due to downwash and mixing of unsaturated air into the fog (helicopter--fixed wing downwash mixing).
3. Seeding with hygroscopic materials to produce larger droplets and/or evaporate existing small droplets.
4. Heating of fog by jets or plumes of air to evaporate droplets.
5. Injection of charged particles to enhance coalescence and/or precipitation.

briefly discussed in the following subsections. This report emphasizes charged particle techniques and a more complete discussion of this technique is given in Section 3.0.

2.1.1 Evaporation Suppression

Visibility improvement in fog by the technique of evaporation suppression is applicable in cases where fog derives its water for formation from underlying canals, lakes, and other small bodies of water. These fogs form by cool air from the land mixing with saturated air over the water surface. Evaporation suppression is achieved by spreading a monomolecular film of a chemical, usually an alcohol (C_{16} to C_{23}), over the water surface. These chemicals can be spread in many physical forms, such as powders, emulsions, and solutions. The amount of alcohol required per area per day [1], to maintain a monomolecular film, increases with increasing wind velocity. Laboratory studies have shown that the ability of alcohols to suppress evaporation increases with increasing hydrocarbon chain length and decreases with increasing film temperature. The long-chain, fatty alcohols, such as hexadecanol and octadecanol are usually utilized because they are nontoxic to both plant and animal life, and their films offer only slight resistance to diffusion of gases other than water vapor.

Some field work has been done on evaporation suppression as a means of water conservation in the United States, but very little has been done to explore it as a mechanism for preventing fog formation. The few experiments which have been completed [2] indicate that it could be a valuable tool for fog prevention. Tests [3] conducted in Panama were successful in suppressing fog and maintaining continuity of Canal traffic on any night after application of the suppressant. However, statements that the Canal would definitely have been closed if no suppressant were applied cannot be made because an insufficient number of tests were conducted to statistically verify this statement.

Evaporation suppression by spreading monomolecular film layers over water surfaces has successfully reduced evaporation from water surfaces by 70 to 80 percent [1]. Consequently, it appears that evaporation can

be reduced enough to keep the water content of the air well below saturation, in the region immediately above the water surface. It seems reasonable to conclude that with proper engineering, evaporation suppression by the use of long-chain alcohols may well solve a substantial number of the fog problems encountered at airports located near small bodies of water.

2.1.2 Fog Dispersal Using the Principle of Downwash Mixing

The downwash from helicopters which pumps dry air from aloft into the fog has been utilized as a fog dispersal technique. In some cases, seeding agents are added to the downwash to enhance the drying effect. The helicopter, during clearing operations, either hovers or moves slowly forward in the clear, dry air above the fog layer. The aerodynamic action of the helicopter rotor(s) forces this clear, dry air downward into the fog layer to distances on the order of 152 to 305 m (500 to 1000 ft), the exact distance being dependent upon atmospheric conditions and the type of helicopter used. The downwash air entrains and mixes with the fog droplets which are totally or partially eliminated by evaporative mixing. The helicopter clears a path 10 to 20 times wider than the dimension of its own rotor(s). The exact dimensions of the cleared space are, of course, strongly dependent on the entrainment-mixing process.

Near the ground the downwash interaction with the surface results in noncomplete mixing compared to the free-air situations. Clearing, in this case, does not occur throughout the total wake region. The portions cleared and the extent of clearing are temporary and highly dependent on flight conditions, on the physical characteristics of the fog, and on the thermodynamic state of the atmosphere.

The use of helicopter downwash to clear radiation-type ground fog for tactical military purposes appears to be practical and effective. Indications are that helicopters might also be used with some degree of success to clear airfield runways, the degree of success depending on prevailing meteorological conditions and the amount of available equipment.

2.1.2.1 Experimental Results

Hover experiments reveal that helicopters are capable of clearing lengths of 122 to 853 m (400 to 2800 ft) downwind of the hover position. This expanse of clearing can be achieved after approximately 10 minutes. The largest clearings are generally observed in fogs shallower than 76.2 m (250 ft) and for tests conducted approximately one hour prior to the natural dissipation of the fog. Fogs of greater vertical extent and at earlier periods of their life cycle are not as amenable to dissipation. Further definitive research is required, however, before any results can be categorically presented as fact.

The amount of clearing has also been found to depend on flight path and pilot experience and proficiency. Using helicopters has been relatively unsuccessful to date in fully clearing the total extent of a runway. Although visibility enhancement is observed well beyond the boundaries of the fully cleared zones, few attempts have been made to determine the size of the affected regions or to assess the degree of the enhancement.

The semi-quantitative information obtained from the literature search, relative to helicopter hover experiments, can be summarized as follows. It has been ascertained that the wake penetration distance of helicopters varies from approximately 152 to 305 m (500 to 1000 ft.) and the time required to attain steady-state clearing conditions ranges from 2 1/2 to 10 minutes. The ratio of the cleared volume to the down-transported volume of air at the rotor level is 1.8 to 8.7. For every part of air that is originally down-transported across the rotor(s), some 3 to 10 parts of air are entrained and mixed into the wake air from the surrounding environment. The wind velocities from the rotor jet downward and over the ground associated with the above measurements are typically between 2.25 to 8.94 m s^{-1} (5 to 20 mph) with gusts to 17.9 to 22.4 m s^{-1} (40 to 50 mph).

2.1.2.2 Conclusions and Recommendations for Downwash Techniques

Based on the above reported observations, it would appear that helicopters operating within well-designed flight patterns may be capable

of maintaining a clear zone, in naturally occurring fog, up to depths of approximately 61 m (200 ft). Whether a sufficient area of a standard runway to permit uninterrupted aircraft operations under normal wind and turbulence conditions can be cleared remains to be demonstrated.

2.1.3 Use of Hygroscopic Material for Fog Dispersal

Warm fog dispersal using hygroscopic particle seeding was first established on a sound scientific basis by the pioneering work of Houghton and Radford [4] and has been the subject of intense numerical modeling and experimental research in recent years (e.g., Jiusto, et al. [5]; Silverman and Kunkel [6]; Kunkel and Silverman [7]; Kornfield [8]; and Smith, et al. [9]). The seeding material is typically dispensed from aircraft. The flight plan usually consists of single or multiple passes with fixed- or rotary-wing aircraft at some specified distance upwind of the targeted area. Early experiments used sodium chloride as the seeding agent. The corrosive nature of this material, however, makes it unsuitable for operational use in populated areas. Application of microencapsulation technology to warm cloud seeding agents (Nelson and Silverman [10]) has now made it possible to use noncorrosive material, such as urea, which may permit broader utilization of hygroscopic materials.

In aircraft operations, the colloquial term "fog dispersal" means improving the visibility or visual range through fog to regulation landing "minimums." Trabert [11] derived the following expression for visibility in fog:

$$V \sim k \frac{r}{\omega}$$

where ω is the liquid water content, r is the drop radius, and k is a constant. From this expression, it is obvious that either of two approaches may be used for increasing visibility: the average droplet radius may be increased or ω may be decreased. The concept of seeding a fog with hygroscopic material may be directed toward either or both of these ends.

The equilibrium vapor pressure over aqueous solutions of hygroscopic materials is less than that over a similar surface of pure water by an

amount that is dependent on the solute concentration. Natural fog droplets can exist only at relative humidities that are very near saturation and in most cases slightly above saturation. If small particles of hygroscopic materials are introduced into a fog, they nucleate droplets and then by extracting water vapor from the atmosphere these droplets grow either to equilibrium with their surroundings or fall to the surface. This leaves the atmosphere slightly subsaturated relative to pure water and the natural fog droplets evaporate. If sufficient water is absorbed by solution droplets, the natural fog droplets will completely evaporate leaving only equilibrium solution droplets.

Scientists, therefore, can replace the natural fog with one consisting entirely of solution droplets and, within limits, can exercise available options to create a new fog having physical properties of their own choosing. For example, by controlling the size distribution of the hygroscopic particles, scientists can produce a fog that consists of a small concentration of large droplets rather than the naturally occurring large concentration of small droplets without significantly altering the liquid water content; therefore, one can increase or improve visibility. By selecting even larger particle sizes, one can cause the solution droplets to grow to such dimensions that they quickly fall to the surface, thereby reducing ω and increasing visibility. In all cases, care must be taken to avoid introducing extremely fine hygroscopic nuclei, which will produce their own stable fog having even poorer visibility than those occurring naturally.

2.1.3.1 Theoretical Studies

Numerous theoretical studies [4,5,6,7] have been performed to determine how the options available through variations of hygroscopic material, particle size, particle concentration, and seeding rate will affect the rate, extent, and duration of visibility improvement. These investigations range from calculations based on simple growth equations and Stokes' drag law (Jiusto [5]) to complex Eulerian computer models that include the effects of coalescence, radiative, and convective heat exchange, and horizontal and vertical diffusion (Silverman [6]). General conclusions arrived at from these studies are:

- The most important property of a hygroscopic seeding agent is that it maintains a relatively low equilibrium vapor pressure even when the particle becomes very dilute. Deliquescence at low humidity is not necessary and usually undesirable. Mechanically, the material must be of such a nature that it can be dispersed without significant aggregation or fracturing into undesirable particle sizes. Chemically, it must be noncorrosive and ecologically safe.

- As the particle size of the seeding agent increases, total mass of the material required to dissipate a fog of given liquid water content also increases. This result stems from the increased rate of fallout of the larger particles which reduces the residence time of particles in the fog and causes the solution droplet to reach the surface before it becomes dilute.

- Larger artificial nuclei, which are required in smaller concentrations but higher total mass, produce clearing more rapidly than small nuclei because the larger particles settle out of the fog more rapidly and cause a greater increase in the mean droplet radius, thus increasing the visibility.

- For a given size nuclei, visibility improvement increases as the total mass of seeding material is increased. However, this effect is not linear and the rate and extent of improvement decreases as more and more seeding material is added.

- Narrow size distributions of nuclei having the same mean volume radius are more effective than broad distributions. Even with the best commercially available sized material, the spread of the distribution causes the seeding rate requirements to increase by a factor of two over that computed for monodisperse nuclei.

- Turbulent diffusion can impose important constraints on the effectiveness of seeding. Cleared regions persist longer under light turbulence conditions than under strong turbulent conditions. In general, seeding operations with high turbulent diffusion require greater total mass of seeding material. If it is desirable to clear only small areas of fog, large particles that produce rapid clearing are most effective. The rate of clearing becomes less significant if large areas are to be cleared.

- When seeding from aircraft, the high concentrations of hygroscopic material in the aircraft wake cause most drying to occur at upper levels and decrease both the rate of clearing and the maximum visibility at the ground obtainable with a given mass of material. This result may be partially alleviated by use of larger hygroscopic nuclei.

- Some modes of helicopter operation distribute the seeding material more uniformly with height, thus producing improved clearing at low levels.

- If the fog depth is 100 m or less, clearing is accomplished primarily by diffusional growth of droplets. For fogs of greater depth, coalescence of solution drops with natural droplets becomes important.

The general conclusions above are summarized in a qualitative sense. Quantitative results for a range of parametric variations are available, but their presentation is beyond the scope of this review.

2.1.3.2 Field Investigations

Ground-Based Seeding

Houghton and Radford [4] were moderately successful in clearing small volumes of fog (up to 10^6 m^3) by seeding with saturated calcium chloride solution droplets dispersed from surface-mounted spray nozzles. In an attempt to produce rapid clearing, 2.5 grams of large solution drops were used per cubic meter of volume to be cleared. The goal was to obtain a reduced relative humidity of 90 percent in a shallow region immediately downwind of the spray system. This goal was achieved in agreement with theoretical expectations.

Because of the imminence of electronic landing systems in 1938 and the expense of seeding techniques, field experimentation was suspended. A period of nearly 30 years elapsed before substantial reconsideration was given to the field of fog seeding.

In 1968, a Cornell laboratory group under NASA sponsorship re-entered the field and conducted a series of ground-based seeding experiments. Dense valley fogs were seeded from a single point source with small (5 to 20 μm and 10 to 30 μm) diameter sodium chloride and urea particles that were dispersed at a rate of up to 13.6 kg (30 lbs) of dry material per minute. The material was dispersed into the fog by blowing it to altitudes of approximately 61 m (200 ft).

Some visibility improvement was observed in almost all experiments. Because of wind direction changes, the dispensed material did not always

move toward the four transmissometers positioned at the opposite end of the field. For this reason, quantitative data were acquired on less than half of the 25 seeding attempts. Typically, when targeting was accurate, visibility was improved by factors of 2 to 5 times initial values, which were approximately 100 m. These improvements were observed to occur downwind 10 to 25 minutes after release of the seeding material, depending on wind speed. Measurement of droplet size distributions and liquid water content in and adjacent to the seeded region showed, for short reaction times brought about by high wind speed, that minimal visibility improvement resulted from a redistribution of the drop sizes. In certain anomalous cases, the liquid water content was greater in the seeded region. Data acquired for long reaction times showed that visibility improvement was greater and resulted from the combined effects of changes in the drop size distribution and a decrease in liquid water content due to precipitation of large solution droplets.

The results of the experiments are in good agreement with theoretical predictions. In general, however, the experimental conditions were not sufficiently repeatable to permit quantitative comparison of the different materials tested.

Airborne Seeding

Airborne seeding experiments have been performed by the Cornell Aeronautical Laboratory (CAL) group at Elmira, New York in 1968 and summer and fall of 1969 [12,13,14]. More extensive experiments were performed by AFCRL and Meteorology Research, Inc., (MRI) at Santa Rosa (1968) [9,15], Columbia (1968) [9], Lake Port (1969) [9], and Noyo River Valley (1969) [15]. Additional field experiments have been conducted by the Naval Weapons Center, China Lake, California [16]. General conclusions derived from these experiments are summarized below.

- There is general agreement between model predictions and experimental results. Significant clearing has been achieved in approximately half the seeding trials that made use of the most advanced technology currently available. The technique, however, is probably not ready for large-scale airport applications at the present time.

- The technology for sizing and dispersing hygroscopic materials is sufficiently advanced to permit field application for some military operations but has not been substantiated for airport applications. At the present time, the cost of producing carefully sized material is extremely high.

- Turbulent mixing causes significant dilution of a plume produced by a single seeding pass. Two possible solutions are available to cope with mixing: (1) Using large seeding rates of giant hygroscopic particles to cause rapid clearing before significant diffusion takes place. This procedure results in narrow cleared regions that usually disappear rapidly. And, (2) applying seeding material by making numerous parallel passes separated by 50 to 100 m to produce a wide region of relatively uniform distributed nuclei at the fog top. The effect of uniformly distributed nuclei is to decrease horizontal gradients and thereby minimize diffusion rates. To treat large areas, economics dictates the use of small particles which are effective at smaller seeding rates. Because of the smaller particle sizes, clearing usually occurs slowly (15 minutes compared to 4 to 5 minutes for larger particles), but with a larger area treated the clearing persists longer (15 to 20 minutes).

- Successive seedings of the same volume by sequential passes appear to produce better results than a single seeding. This result is also predicted theoretically.

- Seeding can be most effectively applied in the late stages of the fog cycle, at least in valley fog. Experimental dissipation tests conducted, to date, indicate that clearing efficiency improves just before natural dissipation occurs.

- The targeting problem, i.e., that of producing a cleared region at the desired location has not been solved. This problem is associated with the high variability of wind direction and strong directional shear. Because of the targeting problem, this fog dissipation technique is not ready for large-scale application at the present time.

2.1.4 Thermal Fog Dispersal

One of the most successful techniques to date for dissipating warm fog at airfields is the direct application of thermal energy from burners to increase the ambient temperature thereby reducing the relative humidity, causing the fog droplets to evaporate. This technique was successfully applied in England during World War II [17] under a program commonly referred to by its acronym "FIDO" (Fog Intensive Dispersal Of). After

World War II, the U.S. Navy developed and tested a much improved FIDO system at Arcata, California. As a result of these tests, a FIDO system was installed at Los Angeles International Airport. However, it was abandoned in 1953 when it was realized that an effective system was too expensive to warrant routine use by commercial aviation at that time.

Recently, a system which utilizes the exhaust heat and velocity from jet engines (Fabre [17]) was installed at Orly and Charles de Gaulle Airports.

The physical principle involved in the dissipation of warm fog by heating is simple and straightforward. For a certain volume of fog with a known amount of liquid water under given ambient conditions, the amount of heat required to vaporize the fog droplets can be determined. Additionally, sensible heat is needed to warm the air to a temperature which permits absorption of the vaporized fog droplets as well as the water ejected by the jet engines.

In addition to the liquid water content and temperature, the speed and direction of the wind are important factors in theoretically predicting the amount of heat necessary to precipitate a fog. Moreover, practice has shown that the uniformity of heat production and the rate at which it is desired to evaporate the fog droplets become important factors in the amount of thermal energy required [18]. Also, it should be noted that an effective system requires a crosswind component at least as great as 1.54 m s^{-1} (3 knots) to carry the thermal energy over the runway and mix it uniformly.

2.1.4.1 Field Investigations

A scientific program to dissipate warm fog using a thermal system was conducted by the French government. Some aspects of the multiphased and involved program are: (1) Identifying safety precautions imposed by aeronautical regulations, (2) designing the most effective heating system and thermal distribution pattern, (3) defining the optimum underground blower and eliminating hardware problems, (4) making noise measurements, and (5) testing the effectiveness of the system. The major components of the thermal dispersal system are: (1) a jet engine,

(2) a diluting nozzle, (3) a connecting sleeve, (4) a blower outlet grid, and (5) an orientation platform. While each component of the underground system is complex in mechanical details, it is the unique design of the platform which proved essential to the success of the prototype testing.

The location of the blower units is probably the most critical decision in deployment of the system since the units are not mobile and once placed their location is fixed. Therefore, in order to insure runway clearings for all wind directions, two rows of underground units are necessary, one on each side of the runway. In crosswind conditions, only the upwind row is conventionally operated. By adjusting the platform, the heated air can also be directed parallel to the wind direction. This arrangement provides most effective results.

A number of fog measurements made during the testing of the Turboclair system (the code name for the French installation) established that an ambient increase in temperature of approximately 2° C assures clearing of nearly all fogs. A related French study [19] shows that a Turboclair-type installation is marginally beneficial (i.e., benefits barely exceed costs) if installed at one airport, but clearly are beneficial if installed at several airports.

In a study to test the effectiveness of heating techniques, Appleman and Coons [20] used jet engines as heat sources. They computed that to meet aircraft landing requirements for an assumed air volume of 10^7 m^3 and a liquid water content of 0.5 g m^{-3}, 3 x 10^9 cal of heat would be necessary to clear the hypothetical air strip. The experimental project (supported by the Air Weather Service (AWS) and named Project Warm Fog), however, showed that the total heat required, under calm wind conditions, was 1.3 x 10^{10} cal. Although this test was not run under strict scientific conditions, it does support the preceding arguments relative to the effects of thermal energy distribution and water injection from the engines.

2.1.4.2 Additional Reported Results

The literature search clearly indicates that wind speed has a noticeable effect on the vertical distribution of the thermal energy. Kunkel, et al. [21] report that at wind speeds of 1.54 m s^{-1} (3 knots) or less the heated air rises too rapidly to be effective near the ground. Between 1.54 and 2.06 m s^{-1} (3 and 4 knots), maximum clearing occurs above the ground, but significant improvements in visibility also occur at ground level. The height of the thermal plume, however, decreases with increasing wind speed. The exact effectiveness of plumes and the exact distribution of heat as a function of wind speed have not yet, however, been fully explored.

Most experimental results are characterized by high frequency fluctuations in visibility due to patches of fog passing through the cleared region. The fluctuating visibility is caused by incomplete droplet evaporation due to uneven spatial distribution of the heat which is further compounded by the intrusion of fog into the heat plume from above and from the end region of the burner rows. Visual observations, however, have indicated that these fluctuations tend to vanish downwind of the target as more time is available for the heat plumes to mix with the environment and for the fog drops to evaporate.

The degree of clearing is strongly dependent on the heat intensity. Field tests have shown that as the heat intensity increases, the mean visibility improves. Extrapolating these results suggests the feasibility of achieving adequate clearing for Category II (CAT II) landing operations. A definition of the different weather categories for aircraft operations is presented in Table 2-3 [22]. Further discussion of Category I and II definitions is given in Section 3.0.

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TABLE 2-3. WEATHER CATEGORIES OF AIRCRAFT LANDING SYSTEMS

	CATEGORY I	CATEGORY II	CATEGORY III		
			A	B	C
WIDTH	Runway--61 m (200 ft.) plus 22.9 m (75 ft.) on each side	Runway--61 m (200 ft.) plus 22.9 m (75 ft.) on each side	Runway--61 m (200 ft.) plus 22.9 m (75 ft.) on each side	Runway--61 m (200 ft.) plus 22.9 m (75 ft.) on each side	No External Visual Reference
LENGTH	2648.7 m (8690 ft.)	2086.4 m (6845 ft.)	∿ 1615.4 m (5300 ft.)	∿ 1524 m (5000 ft.)	
TOTAL DECISION HEIGHT:	99.1 m (325 ft.)	68.6 m (225 ft.)	30.5 m (100 ft.)	-----	
Decision Height	61 m (200 ft.)	30.5 m (100 ft.)	15.2 m (50 ft.)		
Safety	22.9 m (75 ft.)	22.9 m (75 ft.)			
Pilot's Eye Position	15.2 m (50 ft.)	15.2 m (50 ft.)	15.2 m (50 ft.)		
ROLLOUT ZONE:					
Length	1524 m (5000 ft.)	1524 m (5000 ft.)	1524 m (5000 ft.)	∿ 1524 m (5000 ft.)	
Height	22.9 m (75 ft.)	22.9 m (75 ft.)	22.9 m (75 ft.)	22.9 m (75 ft.)	
TOTAL VOLUME	1.8×10^7 m^3 (6.3×10^8 ft^3)	7.6×10^6 m^3 (2.7×10^8 ft^3)	7.6×10^6 m^3 - 5.0×10^6 m^3 (2.7×10^8 ft^3 - 1.75×10^8 ft^3)	∿ 3.7×10^6 m^3 (∿ 1.3×10^8 ft^3)	
RUNWAY VISUAL RANGE (RVR)	>731.5 m (>2400 ft.)	365.8 m - 731.5 m (1200 - 2400 ft.)	213.4 - 365.8 m (700 - 1200 ft.)	45.7 RVT*- 213.4 m (150 RVT - 700 ft.)	

*RVT is Runway Visual Threshold.

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3.0 FEASIBILITY OF USING CHARGED PARTICLE TECHNIQUES TO DISSIPATE WARM FOG

In this study, particular emphasis is placed on charged particle techniques for dissipating warm fog. The feasibility of utilizing this approach for clearing fog on a routine basis for commercial airline operations is especially stressed. Section 3.0 is, therefore, devoted entirely to a discussion of charged particle techniques.

The literature survey indicates that the charged particle technique is plausible. There are, however, some basic questions which require experimental answers before feasibility can be absolutely established and extensive development of operational equipment can begin. The question of whether the required large charge concentrations and high electric fields in a significant volume of the natural atmosphere to produce noticeable fog dispersal can be established and maintained, must be answered. Although several technologies are available to produce high electric fields and large charge concentrations, considerable developmental work is needed to utilize these on a large-scale operational basis.

Another question which must be answered is one of system efficiency. Estimates of system efficiency reported in the literature [23,24,25] vary widely, i.e., 1 to 100 percent. These and other important questions concerning charged particle fog dispersal techniques will be addressed in following subsections.

3.1 Charged Particle Generator Characteristics

Before addressing the questions posed above, a brief qualitative description of the charged particle technique is given. Reports [23,24,25] have been drawn upon liberally in developing this description. The charged particle generators considered in References [23,24,25] are essentially nozzles through which air flows at high velocities. A needle having a high electric potential relative to the surrounding

nozzle walls produces a corona discharge resulting in the formation of small ions. Reference [26] suggests the following mechanism for particle charging. Ions emitted into the airflow at the nozzle entrance function as nuclei for the formation of charged water droplets during the adiabatic expansion of the saturated air in the diverging portion of the nozzle. In turn, droplets formed on naturally occurring nuclei in the airflow can also interact with the ions to form charged droplets.

Reference [25], however, recommends a charged particle generator which forms droplets separately. These droplets are then ejected into the airflow and carried to the ion production region. Ions then attach to the droplets thus charging them as they pass through this region.

As a result of charge transfer from the small ions to the larger water droplets, the electric mobility of the charge carriers is reduced. The lower mobility particles can then be carried further by the issuing jet of mixed air and droplets than would be possible if the charge carriers consisted only of small highly mobile ions [24]. The reason for this is that high mobility particles escape from the jet near the exit due to electrical forces and return to ground before being propelled to significant heights by the jet momentum.

Physical characteristics of the small droplet-laden, turbulent jet have a significant influence on the effectiveness of fog dispersal systems based on the charge particle principle. Typically, for small turbulent jets [24] the jet path width, d, increases linearly with distance from the nozzle exit, x, at a rate of approximately 0.085 x, Figure 3.1. The jet path width is defined as the distance from the centerline at which the jet velocity decreases to half the centerline value.

However, the jet characteristics are changed by electrical forces. Unipolar charged particles in the jet experience a coulomb repulsive force. This force has a component perpendicular to the axis of the jet as well as parallel and therefore causes the charged particles to fan out rapidly. Particles thus escape from the sides of the jet into the ambient surrounding air and then either follow electric field lines to the ground or more desirably collide with a fog droplet charging it.

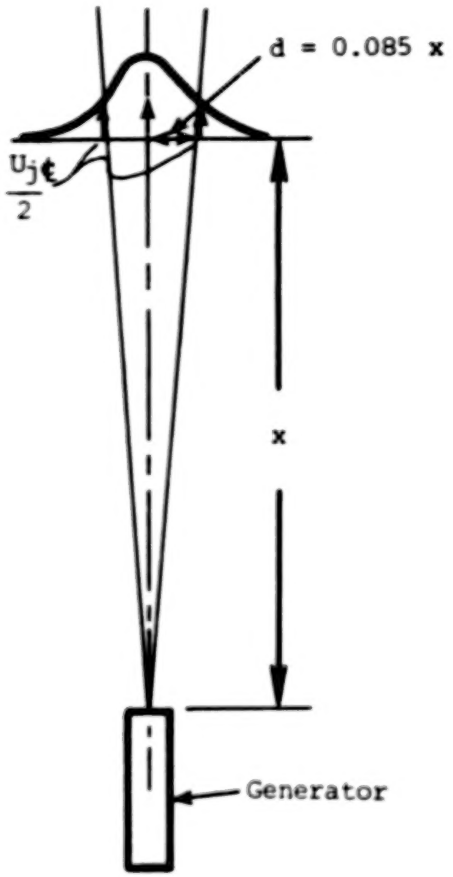

Figure 3.1 Typical velocity profile for a turbulent jet.

The charged fog droplet now also follows the electric field lines to the ground thus achieving the desired goal of fog precipitation.

When exiting the nozzle, particle concentrations are high and therefore result in very strong repulsive forces. These forces, coupled with high mobility, shorten the particle residence time in the jet and thus significantly reduce the height to which particles are propelled by a given nozzle design. Electric mobility and particle concentrations thus strongly influence the height to which particles can be carried by the jet. Fog dispersal for Category II "minimums" require clearing to heights of 200 ft or better. Verification that these heights are achievable with current nozzle technology must be experimentally established.

There are arguments, however, that particle transport by the jet is not necessarily the dominant mechanism of propelling the charged particles

to the required heights. Reference [26] attributes turbulent diffusion of the particles occurring either naturally or due to induced mixing caused by the jets as the major particle transport mechanism. In either event, however, it is unlikely that 100 percent of the charged particles, leaving the jet, will be available to charge fog droplets at significant distances from the nozzle.

The mechanism of charge transfer between the droplets themselves is not fully understood at this time but is another important factor in the performance of a charged particle system. It is generally agreed that after some charge is initially transferred to a given fog droplet, it will then be repelled by other similarly charged fog droplets and/or charge carriers. No further transfer of charge, therefore, occurs by direct contact and thus the maximum charge a particle can receive is restricted by the repelling forces. Of course, variation in the mobility of different droplets will allow further contact and can also alter the state of maximum charge. The range of this variation, although unknown, is expected to be small.

It is also unknown as to whether dispersal of fog occurs due to forced precipitation by electric fields or due to induced coalescence of droplets resulting in precipitation by gravitational fields. Enhanced coalescence may occur between uncharged fog droplets and charge carriers due to dipole induced forces [27]. However, in view of the unipolar nature of the charged particles, it is difficult to believe that after fog droplets have achieved some charge, coalescence in excess of that observed naturally in uncharged fog can occur unless there is a much greater distribution of droplet mobilities. Thus, it appears that the principal fog droplet removal mechanism is simply one of charged particle transport along electric field lines to the ground.

3.2 Theoretical Models

The literature survey indicates that a number of investigators have used the same basic physics and equations to analyze and examine the governing mechanisms of charged particle fog dispersal techniques. However, different assumptions and different values of the pertinent

parameters were employed in the various analyses. These secondary differences in the solutions have apparently resulted in considerable controversy about exactly what can be achieved in practical applications. The basic equations utilized by the investigators are the Gauss's equation, which is expressed in both mks and cgs units, as:

$$\nabla \cdot \overline{E} = \rho/\varepsilon_o \tag{3-1}$$

and

$$\nabla \cdot \overline{E} = 4\pi\rho \tag{3-2}$$

respectively, and the continuity equation

$$\frac{\partial \rho}{\partial t} + \overline{\nabla} \cdot \overline{J} = 0 \tag{3-3}$$

Of the various analytical approaches, two recent analyses are presented in order to illustrate some of these differences.

Reference [23] assumes the array of generators can be analyzed as a plane source. This requires the array of charged particle generators to be spread out over distances which are large compared with the height of the space-charge cloud. Such an assumption may be reasonable for large aerial applications. Edge effects can then be neglected and the charge distribution and electrical field can be analyzed in a one-dimensional Cartesian coordinate system. It is further assumed that due to turbulent diffusion a uniform space-charge is created to an altitude, H. The electric field equation in mks units (Equation 3-1) thus becomes:

$$\frac{dE_x}{dx} = \frac{qn}{\varepsilon_o} \tag{3-4}$$

where q is the charge per particle, n is the particle concentration, and ε_o is the permittivity of free space. With n assumed constant, direct integration yields the electric field as a function of height x;

$$E_x(x) = - qn(H - x)/\varepsilon_o \tag{3-5}$$

where H is the height of the space-charge cloud. It is further assumed that the height, H, is the location where the space-charge concentration in the jet equals the space-charge concentration in the surrounding

uncharged atmosphere. Equation 3-5 shows that the space-charge induced electric field increases linearly with height. It is also assumed that the electric field at the ground never exceeds the breakdown value, 3 x 10^6 volts m^{-1}.

The jet which transports the charge into space is analyzed as follows. The mean speed of the jet is arbitrarily defined such that the momentum in the jet is conserved or

$$U' = U_j r_j/(0.085x + r_j) \tag{3-6}$$

where U_j is the gas speed at the generator nozzle exit, and r_j is the radius of the nozzle.

The rate of loss of the space-charge as a fluid element rises in the jet is given by

$$\frac{d}{dx}(U'qn\pi r^2) = -2\pi rqnzE_r \tag{3-7}$$

Note the original reference has U' removed from the derivative which is incorrect. In this equation, z is the droplet mobility, and E_r is the radial component of the space-charge induced field at the edge of the jet given by

$$E_r = qnr/2\epsilon_o \tag{3-8}$$

Substituting Equations 3-8 and 3-10 into Equation 3-9, and carrying out the integration where $r = 0.085\ x + r_j$, and the boundary condition at $x = 0$ is

$$(qn)_o = 2\epsilon_o E_r(0)/r_j \tag{3-9}$$

The result according to Reference [23] is

$$\frac{n}{n_o} = \frac{1}{1 + [zE_r(0)/U_j]\ (x/r_j)^2\ (0.085)} \tag{3-10}$$

This equation, however, appears to involve several simplifications not described in the reference. A derivation of this equation by the present authors is shown in Appendix 2. Whether Equation 3-10 or that derived in Appendix 2 is used, the results show that as the mobility and/or the

initial charge of the droplets (proportional to $E_r(0)$) increases, diffusion of charge from the jet also increases. The equation developed in Appendix 2, however, predicts a much faster diffusion of charge from the jet.

A somewhat different model is adopted in Reference [24]. This reference assumes the particle generator may be approximated as a point source. Under the assumptions of spherical symmetry and steady-state conditions, the particle concentration and electric field are calculated as a function of radial distance using the electric field equation in cgs units (for purposes of comparison with the original references, the system of units used by each investigator has been retained),

$$r^2 \frac{d(r^2E)}{dr} = - 4\pi\rho \tag{3-11}$$

Integration of Equation 3-11 yields the electric field as a function of radial distance from the source. The equation is solved by first defining Q, the charge crossing a spherical surface as

$$Q = 4\pi r^2 qnv \tag{3-12}$$

where v is given by

$$v = zE$$

Thus,

$$qn = \frac{Q}{4zE\pi r^2} \tag{3-13}$$

Substituting into Equation 3-11 one obtains

$$\frac{d(r^2E)}{dr} = \frac{Q}{zE} \tag{3-14}$$

Multiplying both sides by r^2, recalling $r^2Ed(r^2E) = d(r^2E)^2/2$ and carrying out the integration yields

$$E = \left(\frac{2Q}{3zr}\right)^{1/2} \tag{3-15}$$

Substituting E given by Equation 3-15 into Equation 3-13 results in

$$n = \frac{\left(\frac{3Q}{2z}\right)^{1/2} r^{-3/2}}{4\pi q} \qquad (3\text{-}16)$$

Equation 3-16 indicates that the space-charge around the point source nozzle decays readily as $r^{-3/2}$. Contrasted with Equation 3-16 is the results of the previous model where the charge decays as one over a polynomial in x.

Reference [28] notes from a field study carried out in Panama (to be described later) that the plane source model does not agree particularly well with experiment. The reference points out, however, that this is a result of employing too small a grid of generator units in the experiment, thus not simulating the infinite length array. Reference [24] reports, on the other hand, that reasonable agreement with the same field measurements is achieved if a point source of ions is assumed to be located at a height where the jet centerline velocity is reduced to half its original value, Figure 3.2.

In carrying out the analysis in Reference [24], it is noted that the effective rate of charge from the electron generator was approximately 1/68 of the design value. This may be attributed to a major portion of the charge going immediately to the ground surrounding the generator. Thus, any analysis which does not effectively take in the ground plane cannot provide meaningful results.

Reference [26] assumes that much of the charge will be carried upward by turbulent diffusion. Neither of the two models, however, include the mechanism of turbulent diffusion in the analysis. Thus, the potential transport of charged carriers to greater heights by turbulent diffusion is neglected.

The present authors believe that the state of the art in numerical computations of the atmospheric boundary layer is sufficiently advanced to enable an analysis to be carried out which would include both the ground effects and the diffusive nature of the atmosphere. Development of these more advanced models will still require a better experimental understanding of the charged droplet mobility and the mechanism of

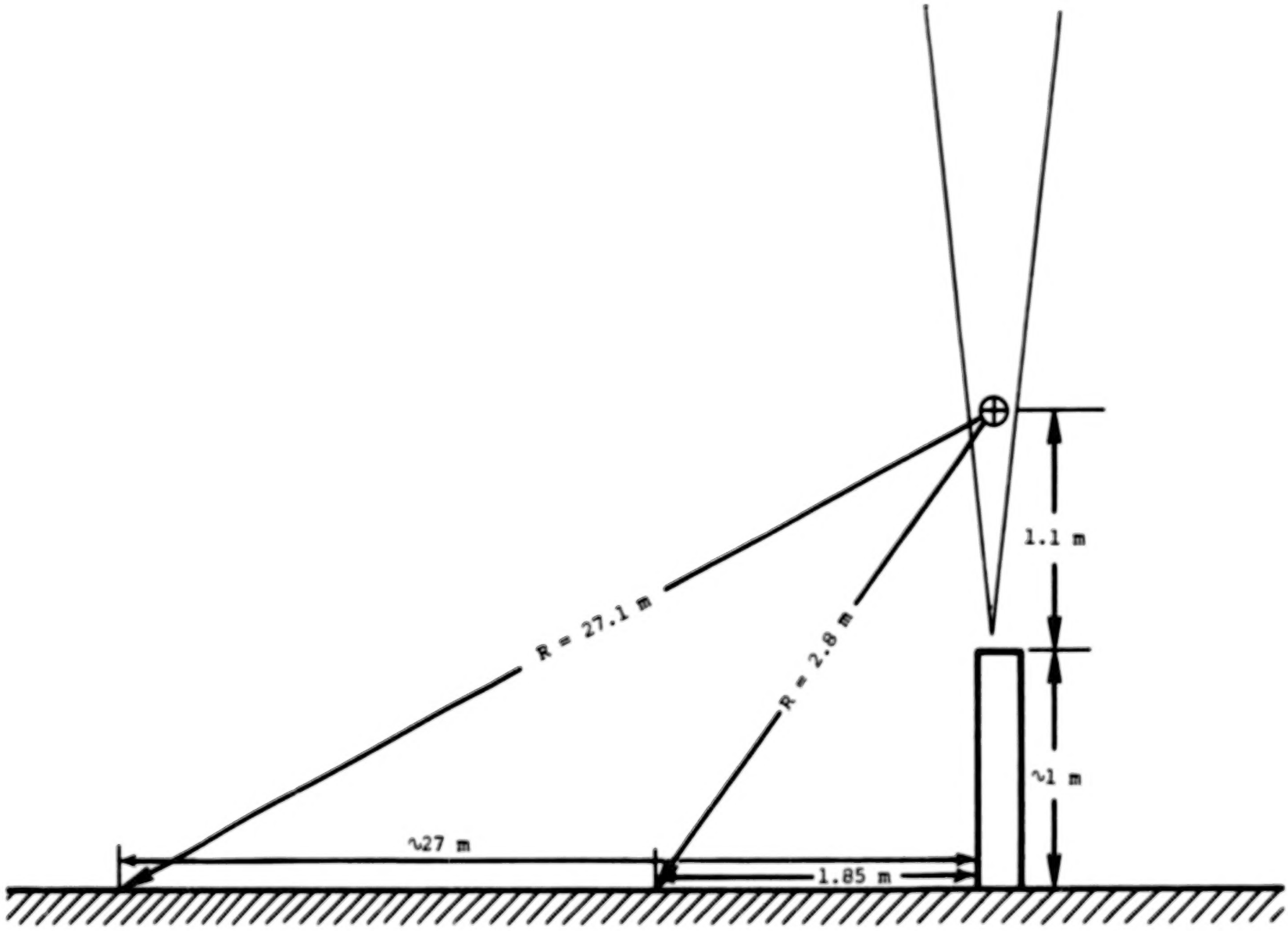

Figure 3.2 Illustrates locations of effective point source of ions which gives reasonable agreement of predicted electric field strength (Equation 3-15) with the electric field measurements taken during the Panama Canal tests [24].

charge transfer from the carriers to the fog droplets. However, even with our current limited understanding of these processes, much can be learned from a numerical model, and work in this area should be carried out.

Until such work is available, the simple one-dimensional models of the type described in References [23] and [24] will be subject to considerable uncertainty. It should be noted that Reference [25] did carry out a numerical study, and an empirical fit to the computed results is discussed later. Unfortunately, this work is not well-documented and the boundary conditions are not clearly specified. It appears, however, that the ground plane effect is not taken into account. Moreover, atmospheric turbulence is not included and the velocity of the jet is an input rather than calculated along with the charge distribution. Work is being carried out to provide a better numerical model of the coupled hydro-electrodynamics of an ion generator nozzle and the jet interaction with the atmospheric boundary layer.

3.3 Discussion of Previous Charged Particle Generator Studies

3.3.1 Jet Penetration

Reported data available on which to base an evaluation of jet penetration of charged particles is pretty much limited to the simple calculations of electric fields and charge densities reported in Section 3.2. A few experiments on a laboratory charged particle dispersal apparatus [25] have been conducted in which the charge density or current (coulombs s^{-1}) was measured to a distance of approximately 40 cm from the jet. No direct measurement of the particle mobility was made. A discrete droplet size of 8 μm was reported [25]; however, droplet size undoubtedly ranged from at least 5 to 10 μm and probably more. Reference [24] reports fitting the experimental data reported in Reference [25] to an exponential curve;

$$I = I_0 e^{-4x} \tag{3-17}$$

where $I_0 = 15.85$ μA is the current at $x = 0$, x is the distance from the nozzle, and I is the current in microamps measured along the centerline

of the jet. Values of the fraction of current left in the jet at various distances from the jet were calculated. A comparison of experimental values of I/I_o [25] with those calculated using the point source model of Reference [24] are illustrated in Figure 3.3. Equation 3-18 was utilized to calculate the I/I_o for the point source model;

$$\frac{n_i}{n_{io}} = \frac{1}{\frac{7.623 \times 10^{11} \; I \; z_i x^2}{Q_j^{2/3} \; U_j^{1/2}} + 1} \tag{3-18}$$

where I is the current flow to the ionizer in amperes, x is the distance from the generator along the jet axis (cm), Q_j is the generator flow rate ($cm^3 s^{-1}$), U_j is the jet exit velocity ($cm\ s^{-1}$), n_i is the charge concentration at distance x along the jet axis (number of droplets cm^{-3}), and n_{io} is the charge concentration at the jet exit (number of droplets cm^{-3}). The point source model agrees reasonably well with the experiment, predicting that approximately two percent of the charge density is left in the jet at 1 m from the exit.

Reference [23], on the other hand, predicts that the current left in the jet at 1 m is still a significant portion of the initial value at the nozzle exit. Reference [23], as noted earlier, assumes that a large portion of the charged particle transport will be due to turbulent diffusion rather than jet propulsion. In support of this theory, it should be noted that experiments carried out at a field site near the Panama Canal [28] indicated that charged particles were carried to heights of at least 10 m. However, reliable estimates of the height to which charged particles can be transported into the atmosphere due to the combined action of natural and jet-induced turbulence and the kinetic energy of the jet is not available at this time. In order to provide at least some insight into the transportation of particles by a jet, a simple model of a turbulent jet in cross flow was investigated. The analysis presented, however, does not include hydrodynamic-electrodynamic coupling effects. Although this important coupling is neglected, the analysis is believed to give a good description of the equipment characteristics required to physically propel particles to the heights

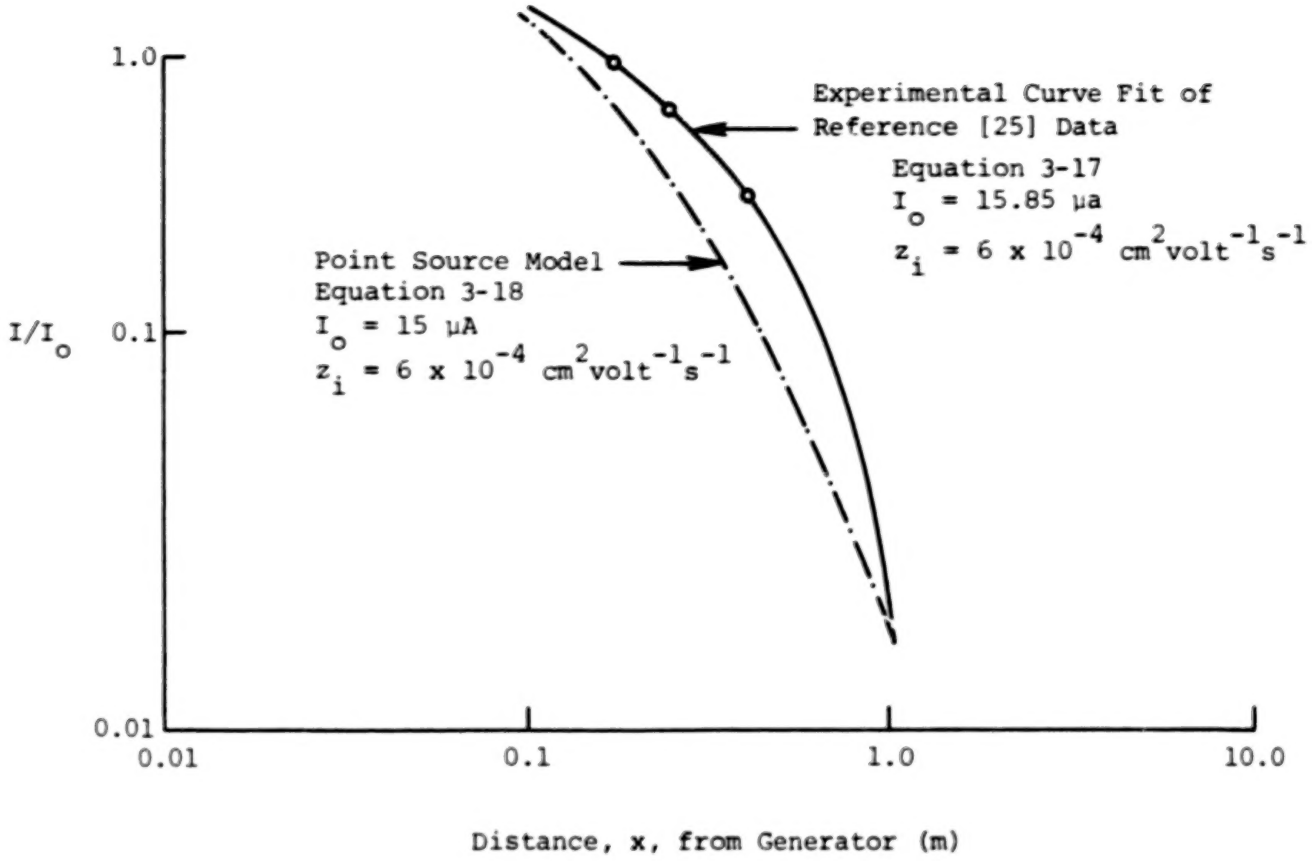

Figure 3.3 Comparison of experimental values of I/I_0 [25] with those calculated using the point source model of Reference [24].

desired if the sole propulsive force is that produced by the momentum of the jet. The effect of natural and jet-induced turbulent diffusion is being considered in an ongoing effort.

Most ground-based jets used for fog dispersal can be characterized by a circular jet diameter, d, with a uniform exit velocity, U_j, issuing at right angles into a free stream moving with a uniform velocity, U_f, shown schematically in Figure 3.4.

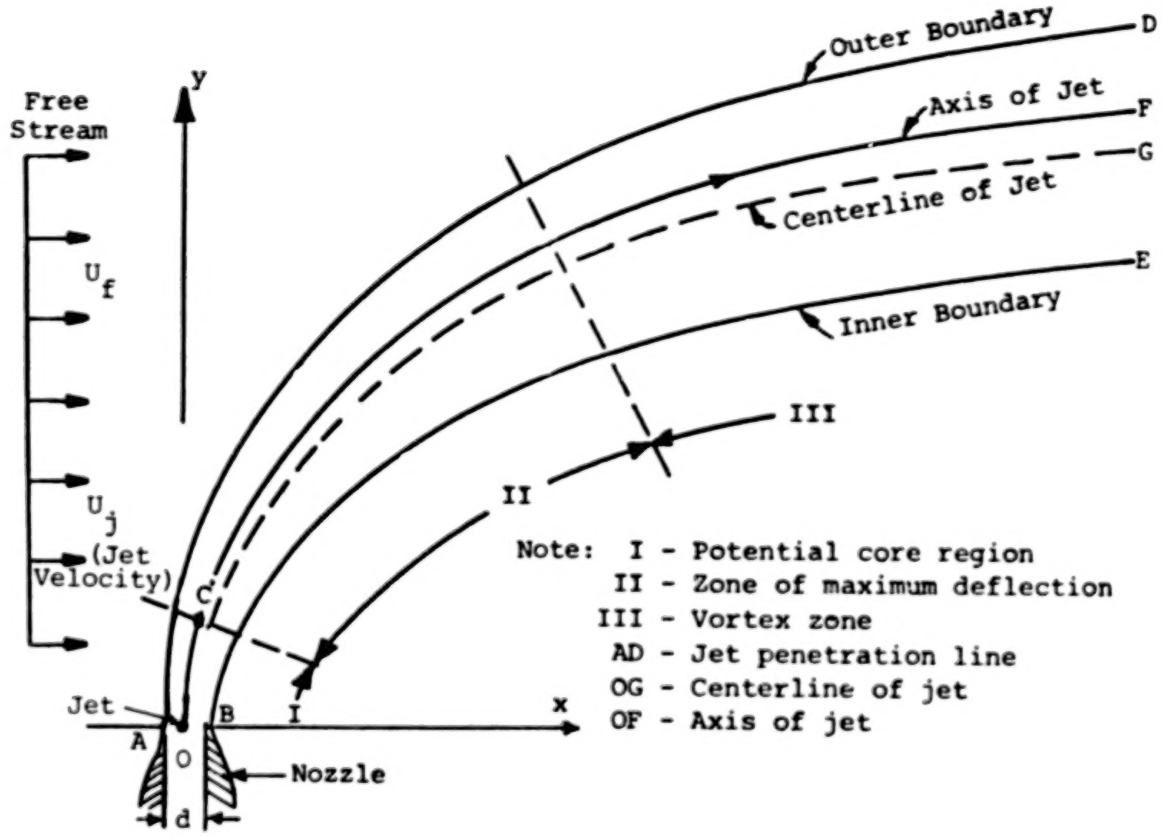

Figure 3.4 Circular jet in cross flow--definition sketch.

Experimental observations [29] have shown that due to the stagnation pressure exerted by the free stream, the jet is deflected. Turbulent mixing develops on the periphery of the jet and deforms the cross sectional shape of the jet. As a result, the jet acquires a characteristic kidney shape. Figure 3.5, reproduced from Abramovich [30], shows the development of this kidney shape where d is the jet diameter and γ is the length of the potential core. As the jet is acted upon by the free

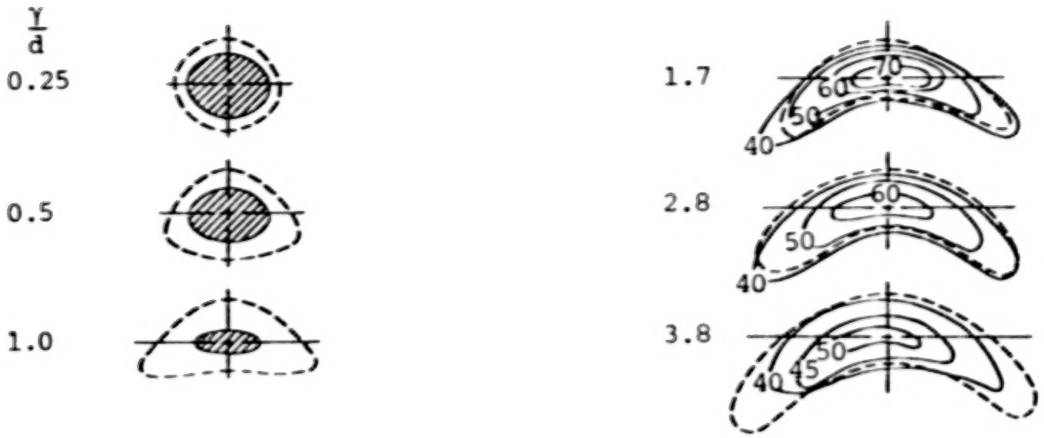

Figure 3.5 Development of a kidney-shaped cross section from a circular jet in cross flow (reproduced from Abramovich [30]).

stream, there is a central region relatively free of shear flow with undiminished total pressure. This region decreases steadily in size and eventually disappears at C. It is specified by the length OC in Figure 3.4 and is generally known as the potential core region. The ratio of the jet velocity to the free stream velocity is represented by the symbol α. Keffer and Baines [29] found that for α greater than about 4, the point C is pushed downwind. From the end of the potential core, the jet suffers a rapid deflection with distance. This region is known as the zone of maximum deflection (see Figure 3.4). The remaining portion of the deflected jet is referred to as the vortex region.

From dimensional analysis and for large values of the jet Reynolds number, $R_e = U_j d/\nu$, the jet penetration for any distance, x, is given by the expression:

$$H/d = f_1(x/d, \alpha = U_j/U_f) \tag{3-19}$$

where H is the penetration height, and x is the distance in the downwind direction.

Pratte and Baines [31], from their study of a 0.4 cm (0.158 in.) diameter jet in a 1.22 x 2.44 mm (4 x 8 ft.) wind tunnel for α from 5 to 35, found that the relation between H and x for the outer boundary could be expressed by the empirical equation:

$$H/\alpha d = 2.63(x/\alpha d)^{0.28} \quad (3\text{-}20)$$

The inner boundary is described by the equation:

$$H_i/\alpha d = 1.35(x/\alpha d)^{0.28} \quad (3\text{-}21)$$

and the centerline by the equation:

$$H_c/\alpha d = 2.05(x/\alpha d)^{0.28} \quad (3\text{-}22)$$

Several calculations of the centerline position using Equation 3-22 were carried out. The diameter of the jet was varied from 0.01 to 0.254 m (0.39 to 10 in.) while the free stream velocity, or ambient crosswind velocity was varied from 1 to 10 m s^{-1} (2.25 to 22.4 mph). Several values for the jet velocity were used; namely 265 m s^{-1} (593 mph), 331.3 m s^{-1} (741 mph), and 447.3 m s^{-1} (1000 mph). Figures 3.6 through 3.8 illustrate the results obtained. Figure 3.6 shows the effect of free stream velocity on the jet (centerline) penetration height. As the free stream velocity increases, the jet penetration decreases. Ambient wind speeds during fog conditions most often range from 0 to 3.58 m s^{-1} (0 to 8 mph) but have been observed as high as 8.9 m s^{-1} (20 mph) [32] during advection fogs. Any ground-based charged particle system used to disperse warm fog should be capable of transporting the charged particles approximately 61 m (200 ft.) above the surface under ambient wind conditions. Increasing flow velocity and/or nozzle diameter increases the penetration height (see Figures 3.7 and 3.8). However, increasing nozzle diameter or jet velocity increases power requirements.

The predicted results shown in the figures correlate fairly well with experimentally observed clearing heights of from 15.25 to 22.9 m (50 to 75 ft.) [32]. This may be fortuitous, however, because the above analysis neglects the effects of the coulomb repulsion forces of the charged droplets. Moreover, the role played by natural or artificially produced turbulence in diffusing the particles to the desired heights is also neglected. A good understanding of the physics of a charged, turbulent jet is therefore necessary to advance the state-of-the-art of charged particle fog dispersal.

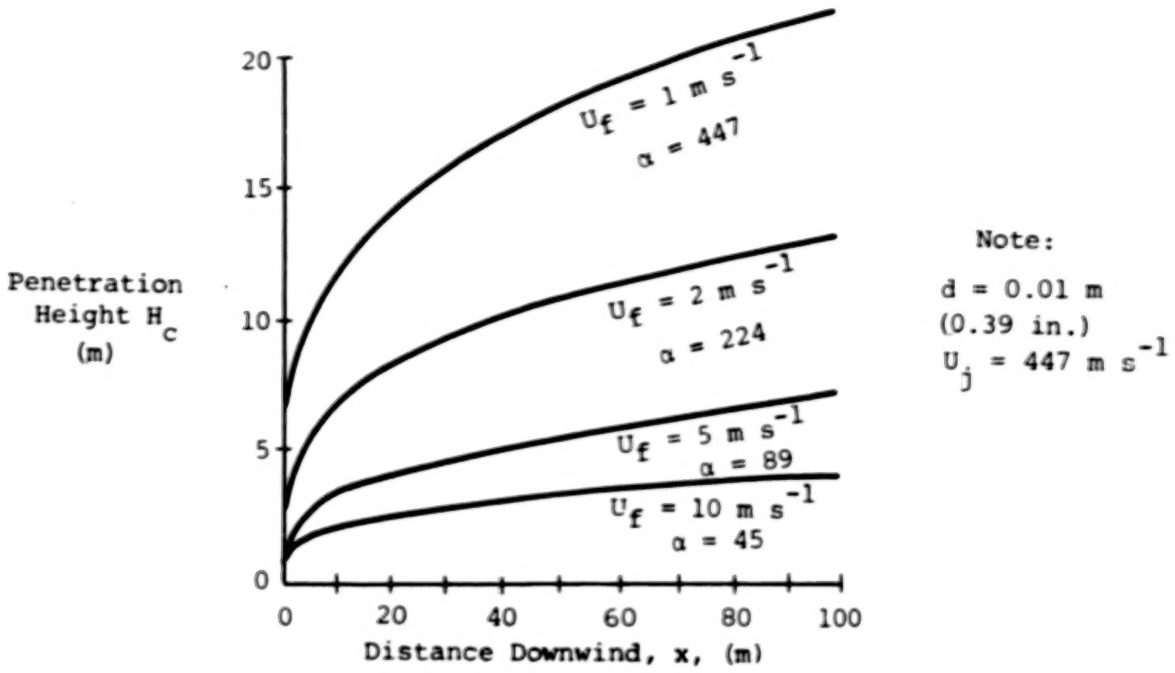

Figure 3.6 Penetration height of jet centerline as a function of distance downwind.

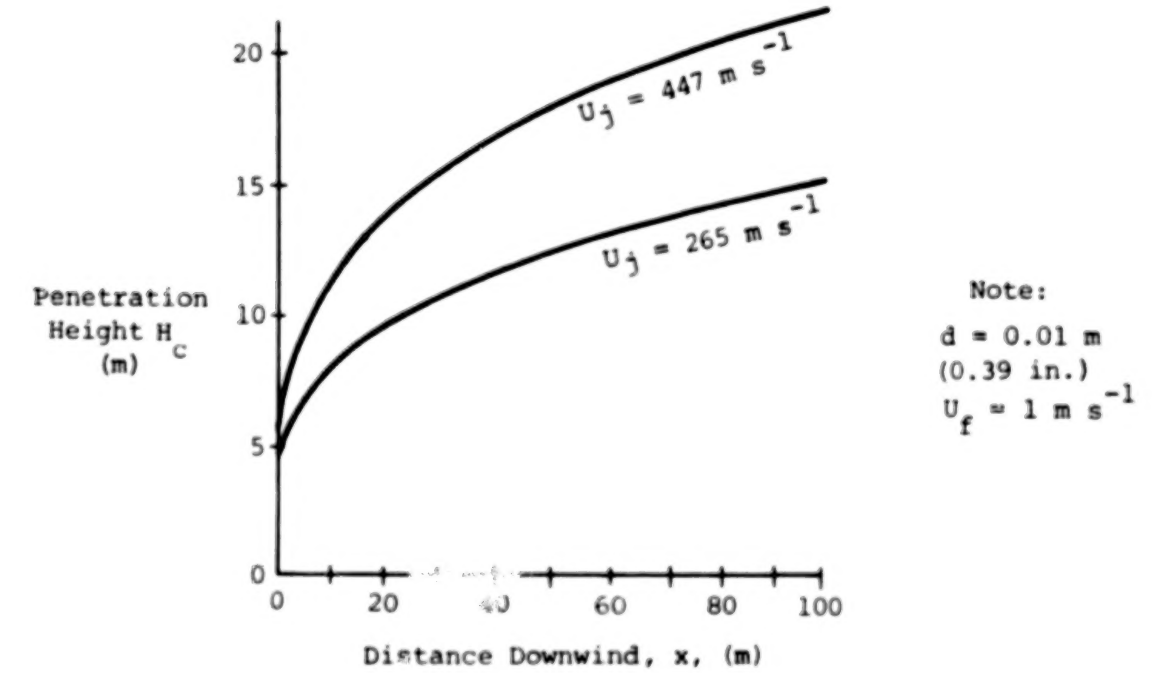

Figure 3.7 Penetration height of jet centerline as a function of distance downwind.

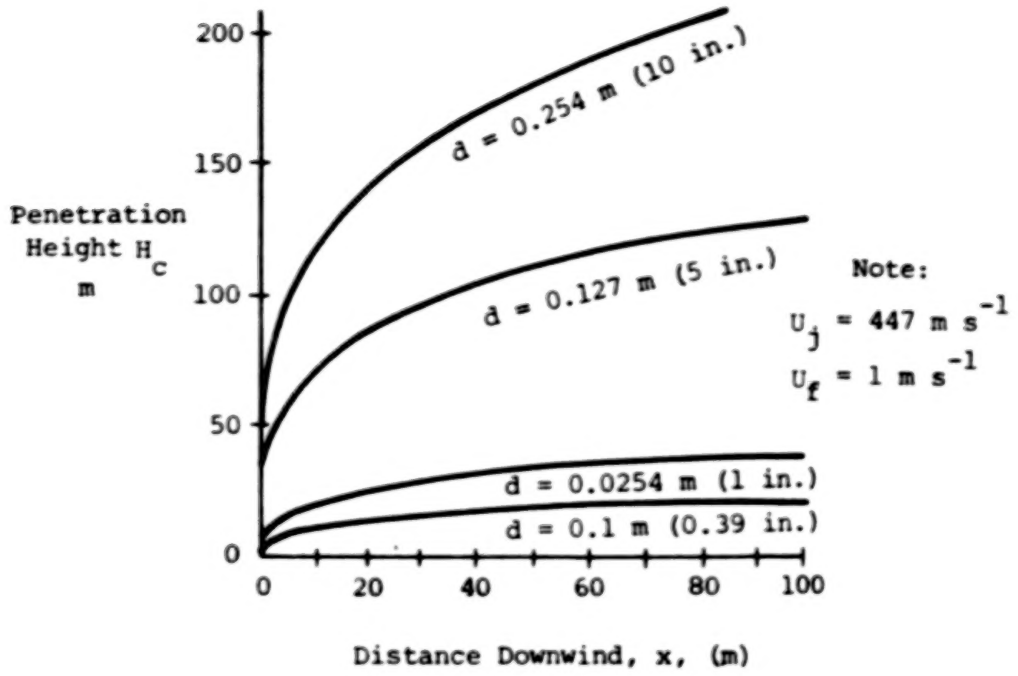

Figure 3.8 Penetration height of jet centerline as a function of distance downwind.

One of the important parameters involved in the overall assessment of any charged particle system is the charge carrier mobility which depends on droplet size. Reference [23] estimates the drop size leaving the generator used in their experiments is approximately 0.1 μm. Reference [33] reports for similarly designed nozzles that droplet sizes in this range are possible. However, it must be emphasized that there is no reliable experimental data to confirm these estimated droplet sizes, i.e., 0.1 μm range. Jet visibility in itself is not a good indicator of the drop size distribution involved. It is possible that only a few large droplets could make the jet visible while the mean droplet size could be subvisible. Gelatin slide techniques were used for drop size measurements during the Panama Canal tests [28]. Droplets in the 0.1 μm size range were not detected. However, current slide/microscope techniques are not capable of detecting droplets sizes in this size range. Improved droplet size measurement techniques are required for future experiments to be effectively analyzed.

The question of droplet evaporation after emission from the generator should be analyzed. It is quite likely that the droplets would evaporate in a dry atmosphere. However, most fogs form in quite saturated environments. Even in a saturated environment very small droplets will evaporate, to a certain degree due to the "curvature effect." This effect will probably not, however, significantly decrease the size or number of particles.

The possibility exists that if a charged droplet does evaporate significantly, it may disintegrate into smaller highly charged droplets. In this case, the amount of repulsive force is greater than the surface tension forces and droplet breakup occurs. Only actual measurements of the charged droplet's size and mobility could determine whether or not this is occurring. It is doubtful, however, in a fog, where the air is saturated, that evaporation would significantly effect the droplet size distribution or mobility. Here again, actual measurements of the charge, droplet size, and charge distribution are necessary to determine if evaporation is significantly effecting the charged particle fog dispersal processes.

3.3.2 Electric Charge Concentration Decay in the Jet

One important question which must be addressed when analyzing charged particle techniques is the residence time of the charged particles in the jet. If a significant fraction of the charged droplets are carried to or diffuse to heights of approximately 20 to 30 m, then the potential for fog droplet charging and subsequent migration of the fog droplets to the ground is significantly enhanced. The uncertainties in charge carrier mobility and whether the droplets evaporate, make it difficult to ascertain whether charged droplets can be carried to these heights or whether they very quickly escape from the jet as it exits the nozzle. Charge concentration decay should be studied experimentally in a more direct fashion than has been done in previous studies. Indirect measurements such as measuring the electric field or the charge density either in chambers or in the atmosphere and inferring mobility are probably not sufficient to establish the needed information. Charge

concentration and charged particle mobility should be experimentally determined as a function of distance along the jet axis to distances of at least 30 m from the nozzle exit.

In a turbulent jet, the velocity profile is approximately Gaussian (see Figure 3.1), and the charged particles spread out from the jet centerline under the influence of forces created by space-charge. The particles are rapidly transported into the lower velocity air at the edges of the jet. If mobility is high, many of the charged particles will be driven out of the jet very close to the generator where they have only a short distance to travel before reaching the ambient surrounding air. The assumption that the charge particles stay in the jet and are transported along with the fluid with 100 percent efficiency and that there is no slip loss within the jet, is unrealistic. It has been argued in Reference [24] that for small ions the concentration decay of charged particles in a turbulent jet is produced essentially by space-charge repulsion. Using equations from Reference [24], the values of the centerline fraction of ions left at various distances x have been calculated for the different generator designs described in References [23] and [25]. The results of the calculations are tabulated in Table 3-1. Note both generators have been analyzed using the point source model.

TABLE 3-1. FRACTION OF CHARGE n_i/n_{i0} LEFT IN THE JET AS A FUNCTION OF THE DISTANCE FROM THE GENERATOR

Gun	I (Current), uA	Z_i (Mobility), $cm^2 stat\ volt^{-1} s^{-1}$	x (Distance), m N_i/N_{i0}						
			0.032	0.1	0.32	1.0	3.2	10.0	32.0
Reference [25]	15	0.18	0.95	0.66	0.16	0.019	0.002	--	--
Reference [25]	15	3.00	0.53	0.10	0.011	0.001	--	--	--
Reference [23] large	100	0.18	0.999	0.993	0.94	0.59	0.13	0.014	0.001
Reference [23] small	17	0.18	0.998	0.983	0.86	0.37	0.056	0.006	0.001

The information presented in Table 3-1 indicates that the charge in the jet decays rapidly. For the large generator of Reference [23], only 13 percent of the charge is left in the jet at 3.2 m. For the charged

particle generator used in Reference [25] with I = 15 μA, 2 percent of the charge is left in the jet at 1 m.

It should be pointed out that if the drops were evaporating this would tend to increase the electric mobility and therefore enhance the rate at which the charged particles escape from the jet. However, in view of the fact that the charge particles are computed to escape rapidly even without evaporation, evaporation should not change the performance charateristics of present day generators. Actually, the assumption that the charge carriers are on the order of 0.1 μm in size with a mobility equal to 0.18 cm^2stat $volt^{-1}s^{-1}$ is near the most favorable case for the projection of the maximum amount of charge to the greatest distance from the generator. Although the escape of charged droplets from the jet may decrease efficiency, Reference [23] points out that the charged droplets may still reach greater heights through the effects of turbulent diffusion.

3.3.3 Panama Field Studies

A field study at the Panama Canal [28] is probably the most specific study of charged particle fog dispersal techniques to date. In this study [28], the following types of measurements were made: (a) the electric field measurements on the ground at approximately 2 m from each generator at a point and midway between consecutive generators, (b) electric field as a function of height using a balloon-borne, space-charge sensor at the center of the array; however, measurements of space-charge distribution were not made over the entire test array, (c) ground-based visibility in and downwind of the array, and (d) qualitative observations of visibility improvement above the array and at downwind locations.

However, this study did not measure directly the droplet mobility, etc. under actual field conditions. Without this information, the physical mechanism of the fog disperal technique is difficult to validate. Calibration and laboratory verification of what the instrumentation truly measured were not apparent in the reported results. For example, the theory of the balloon-borne, space-charge sensor appears to be correct, in so far, as it describes what happens inside the sensor;

however, the question as to whether a representative sample of the charged fog particles was drawn into the sensor is not validated. Since the outer cylinder of this sensor is grounded, and if the electric fields were as high as those reported [28], the grounded probe could seriously effect the field in its vicinity. These effects will also depend strongly on the droplet mobility which is, as pointed out earlier, unknown. It appears, therefore, that an objective validation of all measurement techniques prior and during the experiment would be beneficial.

Indirect assessment of the fog dispersal mechanism is possible, however, from the Panama experiment as described next. Figure 3.9 illustrates the location of electric field strength and space-charge measurements made during the study. If the spherical model for the charge distribution around the individual generators can be considered meaningful, then the electric field close to the generator should be much higher than between them. Experimental data obtained during the Panama Canal tests [28] and illustrated in Figure 3.9 tend to substantiate this point of view. However, limited measurements taken during these same tests, of the electric field as a function of height, indicate that the plane source model may be the most meaningful. Experimental measurements to date have not indicated conclusively which technique is most appropriate. It is most likely that a combination of both techniques is applicable. The spherical point source technique used by References [24] and [25] is most likely applicable very close to the generator itself while the technique in Reference [23] is probably appropriate at large distances from the generator. The exact technique to be used will probably be fairly complicated and difficult to analyze. Experimental measurements of sufficient number and accuracy should, therefore, be taken to answer the question of which technique is most meaningful.

3.3.4 Decay and Concentration of a Cloud of Fog Droplets

Having looked at the charge decay in the jet, attention is directed to the manner and rate at which charged fog droplets decay in the ambient cloud. There is considerable disagreement among investigators as to

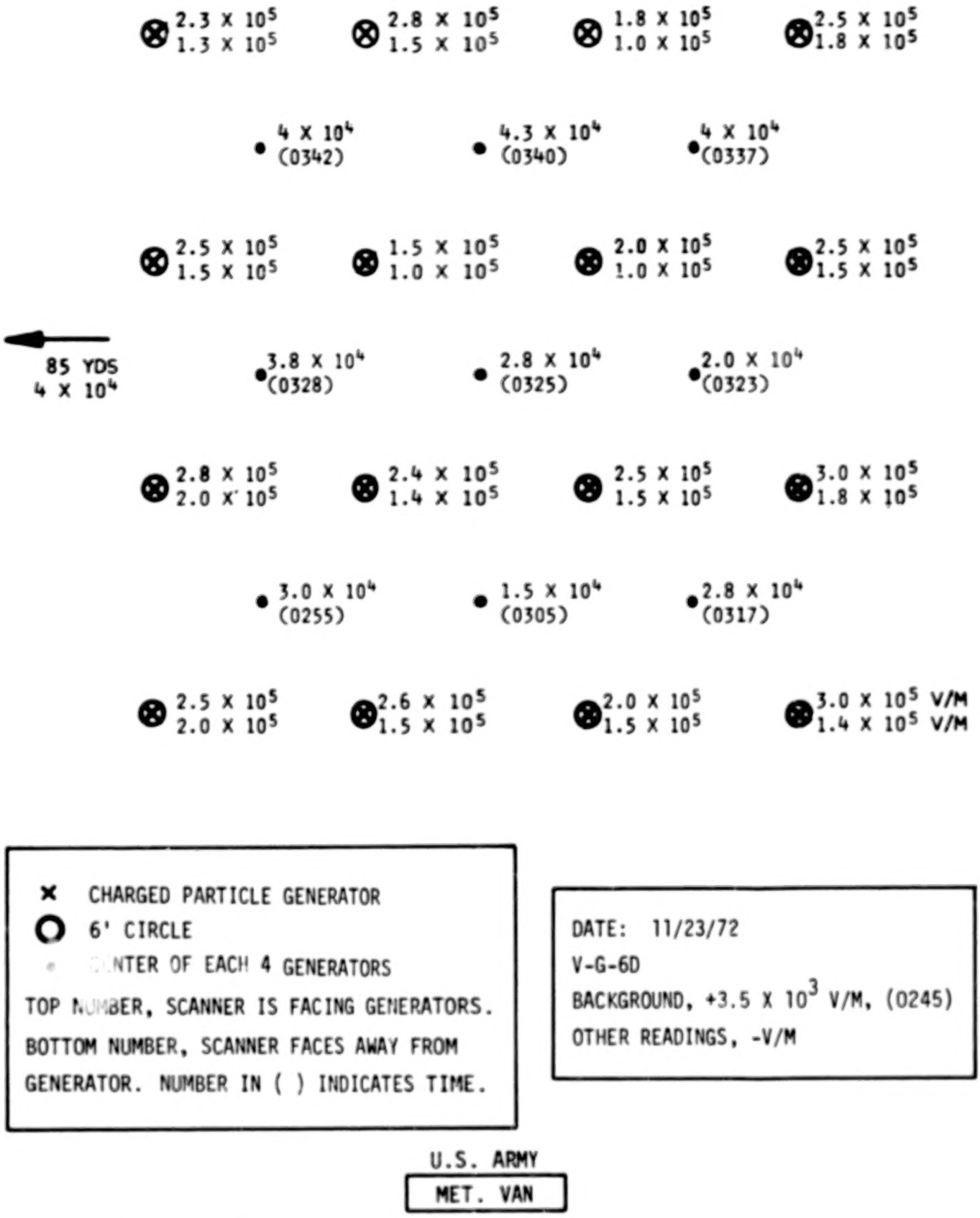

Figure 3.9 Electric field mapping (relative ground-current density distribution).

both the mechanism and the boundary conditions for modeling cloud decay. Reference [24] indicates that for a uniformly charged cloud of particles or droplets within an isopotential enclosure, the decay rate, and hence the concentration reduction rate of the cloud depends only on the cloud properties and not on the potential at the boundary or the geometry of the enclosure. In other words, if the fog droplets could be charged and mixed uniformly, the decay would not depend on either the dimensions or geometry of the cloud but only on the charge and the mobility of the droplets. Reference [23], however, indicates that the electric field at some arbitrary fog cloud height is zero and that the electric field increases linearly to its highest values at the ground. The basic phenomena which must be determined is thus what are the boundary conditions around the fog cloud. Reference [24] gives the following explanation. Certainly the surface can be considered as a ground plane, but since the cloud is not bounded by an isopotential-conducting surface on either of the sides or the top, a homogeneous isopotential model is not strictly applicable. It is possible that if the cloud is much larger than the distance to which the particle generators can propel a significant amount of the charge, then within the time frame of the Panama experiments, there should always be a steep gradient of charged fog droplets on the upper surface and upwind edge of the cloud. Under these conditions, it is conceivable that this steep gradient may function as a quasi-isopotential surface essentially equivalent to a ground potential that is essentially equal to zero potential. Only downwind of the array would this quasi-potential condition not exist. The most meaningful model can, however, only be delineated by detailed measurements of droplet mobility, the extent of cloud charge and the electric field as a function of altitude.

3.3.5 Mechanism for Fog Precipitation

There has been previous experiments which suggest that the important mechanism of fog dispersal is due to coalescence of electrically charged particles and subsequent precipitation by gravitational forces [27]. However, after initial charging, the electric mobility and charge on the fog droplets will be of the same order of magnitude as that of

the charged particles or ions. Therefore, there is reason to believe that the charged fog droplets will repel one another and thus not coalesce, i.e., dipole charge effects will be small compared to coulomb repulsion effects. However, one should remember that the initial stages of fog charging may be extremely important and that dipole induced coalescence between uncharged fog droplets and charged generator particles might well trigger stochastic processes which could play a vital role in the subsequent precipitation process. This needs to be studied further.

3.4 Cost Estimates

The cost of removing fog by charged particle techniques relative to others, in particular thermal, will in all probability be the ultimate factor in the choice of a system for use on a routine basis. A comparison of costs for different fog dispersal techniques must consider the operational and functional requirements of the system and the scheduled arrivals of aircraft. In this way, a cost benefit analysis can be made.

The functional and operational requirements for a fog dispersal technique for CAT I conditions (see Table 2-3, page 17) [22] are that it must increase and maintain visibility to 800 m (one-half mile) equivalent (RVR 732 m (2400 ft.)) or more in the approach, touchdown, and rollout zones of the principle instrumented runway in fog with surface winds from any direction [22].

The fog dispersal technique must provide for a visible path from middle marker or CAT I decision height to touchdown and rollout. The rollout zone is 1540 m (5000 ft.) long.* The width of the zone of increased visibility is the runway width 61 m (200 ft.) plus 22.9 m (75 ft.) on each side of the runway. The width of the cleared zone at the decision height is 305 m (1000 ft.). The height of the cleared zone at decision height is 99 m (325 ft.). This height is composed of 61 m (200 ft.) the decision height plus 15.3 m (50 ft.) for the pilot's eye position with an added 22.9 m (75 ft.) as a safety margin. Figure 3.10

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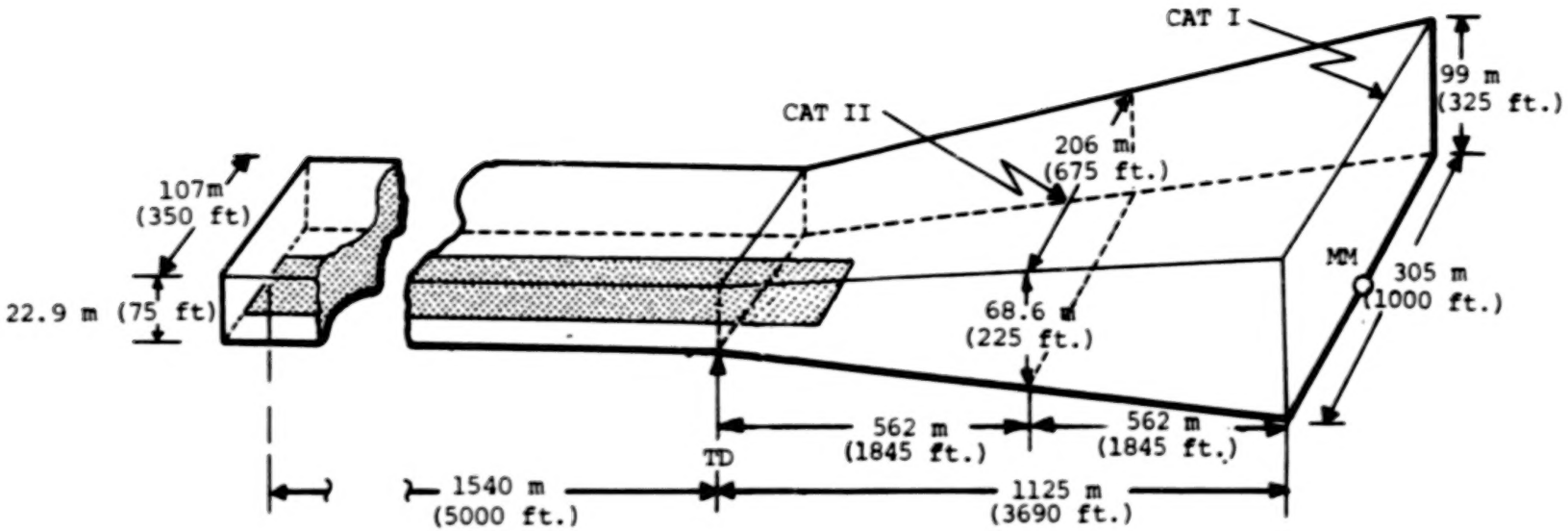
*1540 m (5000 ft.) approximates the rollout distance of a large, heavy jet aircraft with all systems functioning properly.



CAT I VOL = 1.8×10^7 m^3 (6.3×10^8 ft^3)

CAT II VOL = 7.65×10^6 m^3 (2.7×10^8 ft^3)

Illustration is not to scale

Figure 3.10 Proposed region of fog clearance.

illustrates the volume of fog which must be dispersed to permit CAT I operations (i.e., approximately 1.8×10^7 m^3 (6.3×10^8 ft^3)).

For CAT II (see Table 2-3, page 17) [22], the technique must increase and maintain visibility to 366 m RVR (1200 ft.) or more in the approach, touchdown, and rollout zones of the prime instrumented runway in fog with surface winds from any direction.

The fog dispersal system must provide for a visible path from the inner marker or CAT II decision height to touchdown and rollout. The rollout zone is 1540 m (5000 ft.) long. The width of the CAT II zone of increased visibility is the runway width plus 22.9 m (75 ft.) on each side of the runway. At the CAT II decision height, the width of the zone is approximately one-half the width of the CAT I zone at its decision height. The height of the cleared zone at the CAT II decision height is the decision height 30.5 m (100 ft.) plus 15.25 m (50 ft.) to allow for the pilot's eye position plus a safety margin of 22.9 m (75 ft.) for a total of 68.6 m (225 ft.). Figure 3.10 illustrates the volume of fog dispersed to permit CAT II operations (i.e., approximately 7.65×10^6 m^3 (2.7×10^8 ft^3)).

CAT I operations require that either CAT III or CAT II conditions be improved to CAT I; and CAT II operations require that CAT III conditions be improved to CAT II. However, CAT III is divided into three levels, and under the lowest of these conditions (zero visibility), CAT IIIC (see Table 2-3, page 17), aircraft cannot taxi. A separate cost analysis would, therefore, be necessary for these conditions and any comparison of fog dispersal costs or benefits due to CAT IIIC will not be included at this time.

3.4.1 Costs Due to Cancellations, Diversions, and Delays

The major United States airports which have high air traffic count and are scheduled for CAT II ILS installation (or already have CAT II ILS installed) are the most likely to benefit from the installation and operation of a ground-based, warm fog dispersal system. Since many airports would gain from an effective fog dispersal system, it was decided to select, for a more detailed engineering study, only those airports

which would derive the highest potential benefit from the installation and operation of a warm fog dispersal technique.

Screening factors for these airports include the following: average annual number of hours of CAT II and CAT III weather due to fog; air traffic projections for 1981; and projected economic losses due to cancellations, diversions, and delays of scheduled arrivals of United States certified route air carriers because of CAT II and CAT III weather due to fog.

In selecting the airports, it was considered necessary that the airports have a high annual occurrence of fog and a high air traffic density during the hours of fog in order for the fog dispersal technique to be cost-effective. The more aircraft that can land and take-off with a fog dispersal technique in operation, when otherwise the airport would be closed due to fog, the greater will be the benefit to airlines and passengers. Tables 3-2 and 3-3** list the airports selected for potential fog dispersal sites. The average number of hours of CAT II and CAT III A and B weather [22] due to fog are listed based on a ten-year period from January 1, 1956 to December 31, 1965.*** Also, these tables show estimated airline and passenger costs, projected for 1981, associated with disruptions of scheduled arrivals of aircraft of first and second level United States certified route air carriers in domestic and international passenger service due to CAT II and CAT III A and B weather caused by fog. These costs are measures of the potential economic benefits the airport users would realize if the adverse effects of fog on aircraft landings were eliminated by a fog dispersal technique. Not considered are potential benefits which could be derived from foreign flag carriers, general aviation aircraft, military aircraft, and cargo service aircraft.

**1975 dollars are used throughout as a standard in both system costs and benefits for comparison purposes.

***Data from this period was used to insure compatibility with the potential benefit study [34] which used the same ten-year period in forecasting future benefits.

TABLE 3-2. ESTIMATED COSTS DUE TO CAT III A AND B FOG [22]

Cost - These columns are the estimated cost (1981)* associated with disruptions of scheduled arrivals of aircraft of first and second level U.S. certificated route air carriers due to CAT III A&B weather due to fog.

City	Airport	Annual No. of Hours CAT III A&B Fog	Cost to Airlines & Pass. in 1975 Dollars†	Cost to Airlines in 1975 Dollars†
Los Angeles	International	79.1	10,816	2,306
Seattle	Seattle-Tacoma Int'l.	147.0	9,660	2,062
New York	John F. Kennedy Int'l.	32.4	5,169	1,186
Chicago	O'Hare International	26.2	5,157	1,154
Atlanta	The Wm. B. Hartsfield Atl. Int'l.	31.4	3,665	878
Portland, Oregon	International	104.5	3,281	777
Washington	Dulles International	51.0	3,188	782
San Francisco	International	31.2	2,870	721
Baltimore	Baltimore-Washington Int'l.	41.1	2,855	645
Detroit	Detroit Met.-Wayne County	46.6	2,776	627
Philadelphia	International	32.4	2,048	506
New Orleans	International	57.7	1,928	522
Boston	Gen. E. L. Logan International	23.2	1,795	477
Newark	Newark	16.7	1,180	290
New York	La Guardia	16.2	1,137	281
Milwaukee	General Mitchell Field	44.7	1,132	270
Kansas City	Mid-Continent International	24.4	1,117	197
Salt Lake City	Municipal No. 1	35.8	997	284
Covington	Greater Cincinnati	36.8	829	208
Miami	International	11.2	738	190
Cleveland	Cleveland-Hopkins International	21.2	703	200
Pittsburgh	Greater Pittsburgh International	25.8	680	177
Indianapolis	Weir Cook	26.3	645	166
St. Louis	Lambert-St. Louis Municipal	11.9	586	155
Washington	National	15.9	551	137
Buffalo	Greater Buffalo Int'l.	22.0	532	144
Minneapolis	Minneapolis-St. Paul Int'l.	14.4	532	141
Hartford	Bradley Int'l. (Windsor Locks)	43.0	530	121
Columbus	Port Columbus Int'l.	27.4	429	103
Dayton	James M. Cox Municipal	32.8	395	97
Oakland	Metropolitan Oak. Int'l.	36.0	371	90
Anchorage	International	43.5	288	86
Denver	Stapleton International	7.5	259	70
Nashville	Metropolitan	23.3	244	63
Louisville	Standiford Field	16.3	227	58
Rochester	Rochester-Monroe County	15.4	206	53
Birmingham	International	12.4	105	29
Syracuse	Clarence E. Hancock	8.9	92	26

*Projected for 1981.

†In units of $1000.

TABLE 3-3. ESTIMATED COSTS DUE TO CAT II AND III A AND B FOG [22]

Cost - These columns are the estimated cost (1981)* associated with disruptions of scheduled arrivals of aircraft of first and second level U.S. certificated route air carriers due to CAT II and III A&B weather due to fog.

City	Airport	Annual No. of Hours CAT II & III A&B Fog	Cost to Airlines & Pass. in 1975 Dollars†	Cost to Airlines in 1975 Dollars†
Los Angeles	International	121.7	16,647	3,548
Seattle	Seattle-Tacoma International	198.7	13,057	2,787
New York	John F. Kennedy International	69.7	11,109	2,551
Chicago	O'Hare International	46.3	9,109	2,037
Atlanta	The Wm. B. Hartsfield Atl. Int'l.	72.0	8,405	2,013
Washington	Dulles International	101.1	6,316	1,549
Portland, Oregon	International	157.2	4,935	1,169
Baltimore	Baltimore-Washington Int'l.	68.4	4,748	1,073
San Francisco	International	48.5	4,459	1,119
Detroit	Detroit Met.-Wayne County	67.2	4,005	904
New Orleans	International	103.5	3,457	936
Philadelphia	International	53.9	3,413	843
Boston	Gen. E. L. Logan International	43.7	3,373	896
Newark	Newark	31.9	2,248	555
New York	La Guardia	31.8	2,233	552
Kansas City	Mid-Continent International	45.6	2,088	370
Milwaukee	General Mitchell Field	69.5	1,760	419
Salt Lake City	Municipal No. 1	49.4	1,378	392
Covington	Greater Cincinnati	58.7	1,322	333
Miami	International	19.1	1,256	325
Pittsburgh	Greater Pittsburgh International	43.8	1,156	300
St. Louis	Lambert-St. Louis Muncipal	23.5	1,154	306
Washington	National	32.6	1,132	281
Minneapolis	Minneapolis-St. Paul Int'l.	28.2	1,044	277
Indianapolis	Weir Cook	42.5	1,043	269
Cleveland	Cleveland-Hopkins Int'l.	30.1	996	284
Hartford	Bradley Int'l. (Windsor Locks)	72.2	889	203
Buffalo	Greater Buffalo International	36.3	877	237
Anchorage	International	97.8	648	195
Columbus	Port Columbus International	41.0	641	153
Denver	Stapleton International	16.6	575	155
Dayton	James M. Cox Muncipal	47.6	573	141
Oakland	Metropolitan Oakland Int'l.	53.8	555	136
Nashville	Metropolitan	35.4	371	96
Rochester	Rochester-Monroe County	27.8	370	97
Louisville	Standiford Field	25.6	356	90
Birmingham	International	21.6	184	49
Syracuse	Clarence E. Hancock	13.9	141	41

*Projected for 1981.

†In units of $1000.

Table 3-4 is a summary of the top seven airports which have the highest projected costs for 1981 (and therefore would realize the highest potential benefit from a fog dispersal system) together with the projected number of aircraft arrivals during CAT II and CAT III A and B fog conditions [22].

Now that the estimated costs associated with scheduled arrivals have been established, cost estimates of two different warm fog dispersal systems; thermal techniques, and charged particle techniques will be investigated. It should be stated, however, that such systems are inherently complicated and the costs should be considered as only estimates. The first system to be considered is based on the thermal technique.

3.4.2 Cost Estimates of a Thermal Fog Dispersal Technique

3.4.2.1 Modified Passive Thermal Fog Dispersal Technique

The amount of heat required to dissipate warm fog using a modified passive thermal fog dispersal technique and the proper distribution of the heat through specified volumes can be determined by applying available thermal plume technology. Computer programs are usually used [22] to calculate the heat output under various crosswind conditions (normal to runway) in order to determine the horizontal and vertical extent of the thermal plumes under these conditions. Additionally, the width of the cleared volume over the approach and runway zones is determined [22]. The number of therms (1 therm = 2.52×10^7 cal or 100,000 Btu) required to disperse fog for a particular wind direction and speed have also been calculated for the approach, touchdown, and rollout zones for CAT I and CAT II conditions for a major runway at Los Angeles International Airport (LAX) [22]. Tables 3-5 and 3-6 show that a modified passive thermal system must be capable of supplying heat in the CAT I volume 1.8×10^7 m^3 (6.3×10^8 ft^3) ranging from 6×10^{11} cal (24,000 therms) h^{-1} for a 1 m s^{-1} (2 knot) crosswind to 4.7×10^{12} cal (183,000 therms) h^{-1} for a 4.12 m s^{-1} (8 knot) wind parallel to the runway. For CAT II volumes 7.65×10^6 m^3 (2.7×10^8 ft^3), the low and high thermal values are 3.56×10^{11} cal (13,870 therms) and 2.38×10^{12} cal (92,000 therms) h^{-1}, respectively.

TABLE 3-4. PROJECTED ANNUAL COST OF DISRUPTION OF SCHEDULED ARRIVALS OF UNITED STATES CERTIFIED ROUTE AIR CARRIERS DUE TO CAT II AND CAT III A AND B WEATHER CAUSED BY FOG [22]

Airport	CAT II AND III A&B				CAT III A&B			
	Cost ($Million)*		Annual Hrs. Fog	No. Aircraft Arrivals Affected	Cost ($Million)*		Annual Hrs. Fog	No. Aircraft Arrivals Affected
	With Pass. Benefit	Without			With Pass. Benefit	Without		
Los Angeles	16.6	3.5	122	2,191	10.8	2.3	79	1,423
Seattle-Tacoma	13.1	2.8	199	1,778	9.7	2.1	147	1,315
New York (JFK)	11.1	2.6	70	1,348	5.2	1.2	32	627
Chicago (ORD)	9.1	2.0	46	1,339	5.2	1.2	26	758
Atlanta	8.4	2.0	72	1,684	3.7	.9	31	734
Washington, Dulles	6.3	1.5	101	872	3.2	.8	51	440
Portland, Ore.	4.9	1.2	167	1,197	3.2	.8	105	796

Note: The factors (other than the number of aircraft affected) which determine the cost of disruption include, among other things, the estimated family income of the affected passengers, the number of passengers per scheduled arrival and the relative proportion of flight delays, diversions and cancellations for that particular airport. As a result, Dulles, for example, has a higher annual cost of disruption than Portland even though more aircraft at Portland are affected by CAT II and CAT III A&B weather due to fog than at Dulles.

*1975 Dollars

TABLE 3-5. ENERGY REQUIREMENTS/COSTS FOR A MODIFIED PASSIVE THERMAL GROUND-BASED FOG DISPERSAL SYSTEM AS RELATED TO WIND DATA IN CAT II AND III A AND B FOG AT LOS ANGELES INTERNATIONAL AIRPORT (SINGLE LINE GENERATOR SYSTEM), CAT I VOLUME-- 1.8×10^7 m^3 (6.3×10^8 ft^3) [22]

Average Wind (kts) During Fog	No. of Therms Per Hour	Percent Occurrence (True Direction)				Total Percent	No. of Hours Fog Per Year (Average)	Total* Cost @ 7¢ Per Therm/ Hour	Total Cost of Fog Dispersal Per Year	Remarks
Calm	107,872					21.2	25.8	$7,551	$194,816	
Crosswind		N,NNW, NNE		S,SSW, SSE						
2	24,340	2.2		2.7		4.9	6.0	$1,704	10,224	
5	53,605	2.3		3.9		6.2	7.6	3,752	28,515	
8	145,428	.1		.3		.4	.5	10,180	5,090	
Parallel Wind		E,ENE ESE		W,WNW WSW						
2	120,445	7.7		4.1		11.8	14.3	$8,431	120,563	
5	139,305	21.0		12.0		33.0	40.1	9,751	391,015	
8	183,312	3.3		4.1		7.4	9.0	12,832	115,488	
Diagonal Wind		NE	NW	SE	SW					
2	23,688	1	1.3	1.7	.7	4.7	5.8	$1,658	9,616	
5	41,580	1.8	3.4	4.3	1.0	8.5	10.4	2,911	30,274	
8	73,623	.1	0	.5	.1	.7	.9	5,154	4,639	
Fogs With Higher Wind Speeds						1.2	1.4			Not Considered
Totals						100%	121.7		$910,240 (for 100% efficiency)	For 99% Fog Dispersal

NOTE:

1. Assume 80% burner efficiency, fuel cost is $1,137,800 for 99% fog dispersal/yr.
2. If 8 kt. wind/Therm requirement is eliminated, fuel cost/yr. is $961,280 for 90% fog dispersal (109.5 hrs/yr. average). Assume 80% burner efficiency.
3. Crosswind is 90° to runway heading; diagonal wind is 45° to runway heading; parallel wind is parallel to runway.
4. Calculations based on average temperature increase of 3°F. corresponding to a total clearing of the fog within the region of clearance. Fuel estimates are conservative since the visibility inside the region will be greater than required. Therefore, the system fuel requirements can be reduced and still perform to specifications.

* Rates for natural gas (as of July 1975) supplied by Southern California Gas Co., Los Angeles, California.

TABLE 3-6 ENERGY REQUIREMENTS/COSTS FOR A MODIFIED PASSIVE THERMAL GROUND-BASED FOG DISPERSAL SYSTEM AS RELATED TO WIND DATA IN CAT III A AND B FOG AT LOS ANGELES INTERNATIONAL AIRPORT (SINGLE LINE GENERATOR SYSTEM), CAT II VOLUME--7.65 x 10^6 m^3 (2.7 x 10^8 FT^3) [22]

Average Wind (kts) During Fog	No. of Therms Per Hour	Per Cent Occurrence (True Direction)		Total Per Cent	No. of Hours Fog Per Year (Average)	Total* Cost @ 7c Per Therm/ Hour	Total Cost of Fog Dispersal Per Year	Remarks
Calm	70,933			21.2	16.8	$4965	$83,412	
Crosswind		N,NNW, NNE	S,SSW, SSE					
2	13,874	2.2	2.7	4.9	3.9	$ 971	$ 3,787	
5	28,979	2.3	3.9	6.2	4.9	2029	9,942	
8	83,862	.1	.3	.4	.3	5870	1,761	
Parallel Wind		E,ENE, ESE	W,WNW WSW					
2	74,460	7.7	4.1	11.8	9.3	$3212	$48,472	
5	79,073	21.0	12.0	33.0	26.1	5535	144,464	
8	92,639	3.3	4.1	7.4	5.9	6885	40,622	
Diagonal Wind		NE	NW SE	SW				
2	16,480	1	1.3 1.7	.7	4.7	3.7	$1154	$ 4,268
5	37,590	1.8	1.4 4.3	1.0	8.5	6.7	2631	17,630
8	56,607	.1	0 .5	.1	.7	.6	3962	2,377
Fogs With Higher Wind Speeds				1.2	1.0			Not Considered
Totals				100%	79.1		$356,735 (for 100% efficiency)	For 99% Fog Dispersal

NOTE:

1. Assume 80% burner efficiency, fuel cost is $445,920 for 99% fog dispersal/yr.
2. If 8 kt. wind/Therm requirement is eliminated, fuel cost/year is $390,000 for 90% fog dispersal (71.2 hrs.). Assume 80% burner efficiency.
3. Crosswind is 90° to runway heading; diagonal wind is 45° to runway heading; parallel wind is parallel to runway.
4. Calculations based on average temperature increase of 3°F. corresponding to a total clearing of the fog within the region of clearance. Fuel estimates are conservative since the visibility inside the region will be greater than required. Therefore, the system fuel requirements can be reduced and still perform to specifications.

* Rates for natural gas (as of July 1975) supplied by Southern California Gas Co., Los Angeles, California.

The length of a row of continuous heat generators required to clear a runway at LAX in the CAT I specified volume is approximately 6096 m (20,000 ft.). This line will require site survey, excavation, construction, tunneling, etc. Specialized heat generators to provide the required heat output for the various wind speeds would have to be developed and specially manufactured. Additionally, the heat generators in close proximity to taxiways will have to be equipped with blowers. The heat generators would be installed in underground, reinforced, concrete trenches. Engineering cost estimates for construction and installation of such a system are approximated $11,000,000.

Calculations of benefit to cost ratios of such a system are based on an installation period of approximately two years, expected fog dispersal system life of ten years and an annual interest rate of 10 percent. The installation and procurement cost is assumed to be equally divided during the two-year installation period, one-half the total cost for the first year, one-half for the second year. Technique benefits are based on the projected 1981 level of traffic throughout the ten-year life expectancy of the fog dispersal technique. It should be noted that the benefit/cost figures become larger as the life of the technique exceeds the ten-year figure. Benefit to cost information is given in Table 3-7. The operating costs and benefits are for a technique capable of producing clearing in approximately 90 percent of all fog occurrences.

3.4.2.2 Thermokinetic Fog Dispersal System

The installation and operation of a thermokinetic system at LAX will now be briefly considered. The system employs turbojet engines, installed underground, to produce thermal and kinetic energy which heats and mixes the foggy air over the runway to evaporate the fog and improve visibility. A properly engineered thermokinetic fog dispersal technique installed at LAX would probably be capable of improving visibility in fog from CAT III conditions to at least CAT II minimums in the specified CAT II volume of 7.65×10^6 m^3 (2.7×10^8 ft^3). Costs, however, may be prohibitive. Heat systems may also be detrimental to the environment.

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TABLE 3-7. BENEFIT TO COST ESTIMATES FOR MODIFIED PASSIVE CAT I AND CAT II SYSTEMS AT LAX (IN UNITS OF $1,000) [22]

Modifed Passive Cat I

Year Since Initiation	Expected Yearly Cost	Expected Yearly Benefit (3)	
(1)	(2)	With Pass. Benefit	Without Pass. Benefit
1	$5,510	0	0
2	5,510	0	0
3	1,151	$14,982	$3,193
4	1,151	14,982	3,193
5	1,151	14,982	3,193
6	1,151	14,982	3,193
7	1,151	14,982	3,193
8	1,151	14,982	3,193
9	1,151	14,982	3,193
10	1,151	14,982	3,193
11	1,151	14,982	3,193
12	1,151	14,982	3,193

12 year expected value cost: $15,404,000
12 year expected value benefit (including passenger benefit): $76,080,000
(without passenger benefit): $16,215,000

Benefit to Cost Ratios:

4.9 to 1 for airlines and passengers
1.1 to 1 for airlines

Modified Passive Cat II

Year Since Initiation	Expected Yearly Cost	Expected Yearly Benefit (3)	
(1)	(2)	With Pass. Benefit	Without Pass. Benefit
1	$4,372	0	0
2	4,372	0	0
3	537	$9,734	$2,075
4	537	9,734	2,075
5	537	9,734	2,075
6	537	9,734	2,075
7	537	9,734	2,075
8	537	9,734	2,075
9	537	9,734	2,075
10	537	9,734	2,075
11	537	9,734	2,075
12	537	9,734	2,075

12 year expected value cost: $10,311,000
12 year expected value benefit (including passenger benefit): $49,431,000
(without passenger benefit): $10,539,000

Benefit to Cost Ratios:

4.8 to 1 for airlines and passengers
1.02 to 1 for airlines

It is estimated that 20 turbojet engine installations are required to clear the above mentioned volume of foggy air to CAT II minimums. They must be spaced 91 m (300 ft.) apart and located 91 m (300 ft.) from the runway centerline. Engineering cost estimates (1975 dollars) for construction and installation of a thermokinetic fog dispersal system at LAX capable of improving CAT III fog conditions to CAT II minimums (or better) in the specified volume of 7.65×10^6 m^3 (2.7×10^8 ft^3) are approximately $5,000,000. Benefit to cost information for this system is given in Table 3-8 [22]. The operating costs and benefits are for a system capable of producing clearing in approximately 90 percent of all fog occurrences.

3.4.3 Cost Estimates of a Ground-Based Charged Particle Fog Dispersal System

The cost of a ground-based charged particle fog dispersal technique will now be considered. The system will be subject to two principal cost variations. The first source of cost variation is the system size as determined by the number of dispersal units required by airport geometry, meteorological conditions (principally wind speed and direction), and level of visibility criteria. The second source of cost variation will result from changes in unit capability and subsequent changes in spacing to maintain optimum fog dispersal conditions. A fairly good estimate of costs can be made once the above variations have been considered since operating generators have been constructed [23] (assuming no major modifications in design are needed). A one time capital investment of approximately $1,500 (1975 dollars) [23] for each unit is required. It has been estimated that the annualized fuel and maintenance costs is $100 per unit [23].

A simple cost estimate for clearing a typical runway at a major airport is presented below. Visibility criteria levels for CAT II are used. One dispersal unit capability is utilized; i.e., current leaving the unit (as constituted by the stream of charged droplets) of 80 μA [23]. Wind speed is varied from 0 to 3.58 m s^{-1} (8 mph) and directed perpendicular to the runway being cleared. Winds up to 3.58 m s^{-1} (8 mph) coming

TABLE 3-8. THERMOKINETIC CAT II SYSTEM AT LAX USING JET FUEL AND NATURAL GAS [22]

Jet Fuel

Year Since Initiation	Expected Yearly Cost	Expected Yearly Benefit (3)	
(1)	(2)	With Pass. Benefit	Without Pass. Benefit
1	$2,608	0	0
2	2,608	0	0
3	232	$9,734	$2,075
4	232	9,734	2,075
5	232	9,734	2,075
6	232	9,734	2,075
7	232	9,734	2,075
8	232	9,734	2,075
9	232	9,734	2,075
10	232	9,734	2,075
11	232	9,734	2,075
12	232	9,734	2,075

12 year expected value cost: $6,840,000
12 year expected value benefit
(including passenger
benefit): $49,431,000
(without passenger
benefit): $10,539,000

Benefit to cost ratios:

7.2 to 1 for airlines and passengers
1.5 to 1 for airlines

Natural Gas

Year Since Initiation	Expected Yearly Cost	Expected Yearly Benefit (3)	
(1)	(2)	With Pass. Benefit	Without Pass. Benefit
1	$2,508	0	0
2	2,508	0	0
3	490	$9,734	$2,075
4	490	9,734	2,075
5	490	9,734	2,075
6	490	9,734	2,075
7	490	9,734	2,075
8	490	9,734	2,075
9	490	9,734	2,075
10	490	9,734	2,075
11	490	9,734	2,075
12	490	9,734	2,075

12 year expected value cost: $5,702,000
12 year expected value benefit
(including passenger
benefit): $49,431,000
(without passenger
benefit): $10,539,000

Benefit to cost ratios:

8.7 to 1 for airlines and passengers
.8 to 1 for airlines

in a direction perpendicular to a runway are normally rare and this analysis therefore represents the costs required to clear nearly all fog occurrences. The development of any optimum system will ultimately require a cost/benefit analysis for each airport and a determination of the percentage of all fog occurrences to be cleared. Several assumptions are made in this analysis; however, these assumptions are consistent with theoretical and experimental results [23,24,25]. It is assumed that an electric field, E(0), of 10^6 volt m^{-1} [28] is produced by the fog dispersal units. The current required to maintain an electric field of 10^6 volt m^{-1} is given by the following expression [28]

$$I = \epsilon_o E^2(0) z \frac{(LW)}{H} \tag{3-23}$$

where ϵ_o is the permittivity of free space (8.85×10^{-12} F m^{-1}); z is the mobility (10^{-7} m^2 $volt^{-1}$ s^{-1}) [35]; L is the length of the area to be cleared (2086 m (6844 ft.) for CAT II); W is the width of the area to be cleared (107 m (350 ft.) for CAT II); and H is the height to be cleared (68.6 m (225 ft.)) or decision height for CAT II.

Substitution of the above values into Equation 3-23 gives I equal to 2.88×10^{-3} A. Now consider the individual generator capability; namely, that each unit provides 80 μA. Units are arranged so that charged droplets are dispersed vertically into the atmosphere. Under calm wind conditions the number of total units required will be

$$\frac{2(2.88 \times 10^{-3})}{80 \times 10^{-6}} \sim 72 \text{ or } 36 \text{ on each side of the runway.}$$

The unit spacing is then 58 m. The number of units required to dissipate fog in crosswind conditions depends on the wind velocity and time required for visibility to improve to CAT II conditions once the fog dispersal units are turned on. The time required for visibility to improve to 457 m (1500 ft.) (required visibility for aircraft landing) [28] is estimated at 14 minutes.

For 2.24 m s^{-1} (5 mph) crosswind conditions, the wind drifts 1878 m (6160 ft.) in 14 minutes. Therefore, to disperse fog with 2.24 m s^{-1} (5 mph) crosswind conditions requires a matrix of units at a 58 m spacing

in an area 2086 x 1878 m^2 or approximately 1095 units. A similar analysis was carried out for 3.58 m s^{-1} (8 mph) conditions. A synopsis of the results are illustrated in Table 3-9.

TABLE 3-9. COST ESTIMATES FOR A CHARGED PARTICLE GROUND FOG DISPERSAL SYSTEM

Unit Capability	Wind Speed (perpendicular to runway)	Required Unit Spacing	Approximate Number of Units Required	Initial Capital Investment (1975 dollars)	Approximate Maintenance Costs ($100/unit per year)	Approximate Annualized Cost Assuming an 8% Discount Rate and a Ten-Year Equipment Life with No Salvage
80µa	calm	58 m	72	$ 108,000	$ 7,200	$ 29,000
80µa	2.24 m s^{-1} (5 mph)	58 m	1095 (one side)	$1,642,000	$109,000	$365,000
80µa	3.58 m s^{-1} (8 mph)	58 m	1791 (one side)	$2,687,000	$179,000	$543,000

The number of units may, however, be reduced below those indicated in Table 3-9. The units are mobile and could possibly be used in different configurations thus reducing the overall number required. The figures in Table 3-9 do, however, represent a good first approximation to the costs involved. A brief comparison with costs incurred due to cancellations, delays, and diversions (see Table 3-2, page 46) indicates that this fog dispersal technique could be cost-effective for a good number of United States airports. Table 3-2 indicates that there are approximately 25 airports in the United States with annual costs due to cancellations etc. greater than the annualized cost of a charged particle dispersal system capable of dispersing fog in 8 mph crosswind conditions. The installation of a charged particle system would seem to be cost-effective at these airports.

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4.0 CONCLUSIONS AND RECOMMENDATIONS

As a result of the original effort to assess the potential of using charged particle techniques to dissipate warm fog, it was determined that considerable disagreement exists between major researchers on the capability of charged particle fog dispersal techniques. The disagreement stems from the fact that different assumptions and parameter values are used in the analytical models. It is concluded that to resolve this disagreement experimental measurements of the important parameters in question are required. First, however, a very careful evaluation and identification of exactly what measurements are to be made is needed. Then an experimental plan must be written. This plan must clearly state the availability of existing instrumentation to carry out the experiment and what instrument development costs are required. A study to ascertain if possible safety hazards, such as increased electrical activity or fuel ignition during refueling operations would render charged particle warm fog dispersal techniques impractical is also required. A conclusion that safety was jeopardized due to electrical field effects would significantly alter the feasibility of utilizing a charge particle fog dispersal system.

The following are a few recommendations which have resulted from the review of the charged particle technique reported herein. Although each of these recommendations is not entirely accepted by other investigators, the results of this study suggest that the following actions for further investigations of charged particle warm fog dispersal techniques should be taken.

A. A careful evaluation of what is required to carry out a field test should be delineated. The relevance of the major problems concerning charge transfer and particle mobility should be identified and discussed. Both modeling and experimental research aspects should be considered in light of present knowledge.

B. Possible hazards to aircraft operations such as increased electrical activity effects on on-board micro-processing equipment or on fuel ignition during refueling operations should be ascertained.

C. A more complete analysis incorporating hydrodynamic and electrical coupling and advanced turbulence modeling of nozzle flow and the charged particle jet should be developed. Nozzle designs should be optimized based on both analytical and experimental results.

D. There is a need for a thorough study of a single charged particle generator.

   1. There is a need to study what amount of total charge is left in the jet as a function of distance out to least 30 to 50 m.

   2. Measurements need to be made of charge carrier size, electric mobility, and distribution at realistic ambient relative humidities to a distance of at least 30 to 50 m. The charge carrier electric mobility is a crucial factor in all the techniques that have been proposed and should be experimentally measured. There is no hope of improving the credibility of the techniques without some good measurements of the actual carrier mobilities and generator characteristics. Detailed measurements of electric fields and charged densities, as a function of distance from the generator, should also be made.

E. A space charge probe, should be developed and validated.

F. More optical measurements over shorter path lengths should be made in the immediate vicinity of the generators at various locations in the array. It is doubtful that further chamber studies will be beneficial unless the chamber is extremely large and it can be shown that the droplet size distributions used are similar to those of actual warm fogs. The boundary conditions in a chamber are probably so different from those in the open atmosphere that it would be very difficult to simulate actual conditions. Instrument needs and/or modifications and their costs should be accurately ascertained.

G. Microphysical research should be investigated in more detail and if knowledge gaps exist, the appropriate laboratory studies should be undertaken. Adequate drop size measurement techniques should be investigated in order that drop sizes and, hence, mobility can be adequately obtained and assessed with regards to the appropriate techniques and parameters involved.

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APPENDIX 1

LITERATURE SYNOPSIS

The literature synopsis presented here is by no means all inclusive but serves to outline some of the significant reports and articles pertaining to the charge particle fog dispersal technique. A complete bibliography of the articles reviewed is presented in Section 6.0. This section summarizes information such as the reference, the objective, the significant parameters, the technique description, and the author's conclusions.

REFERENCE: Smith, M. H. "The Collection Efficiencies of Highly Charged Water Drops for Uncharged Cloud Droplets," Journal of Applied Meteorology, Vol. 15, pp. 275-281, 1976.

OBJECTIVE: To study the collection efficiencies of highly charged water droplets.

SIGNIFICANT PARAMETERS: Droplet size, collection efficiency, droplet charge, humidity, conductivity of fluid, and electric field.

TECHNIQUE DESCRIPTION: Steady streams of essentially monodisperse drops with different radii were charged to between 70% to 80% of their Rayleigh limit at rates of 100 to 200 per second. These drops were then used to interact with uncharged particles.

AUTHOR'S CONCLUSIONS: For drop charges approaching Rayleigh limit values, the influence of one drop capture extends to several drop radii giving collection efficiencies over 20 times greater than the values pertaining to uncharged drops. Furthermore, these electrical effects become more pronounced as both droplet radii are reduced and their ratio approaches unity.

MERITS OF TECHNIQUE: The technique of using charged droplets to enhance coalescence appears to be an efficient and practical manner of dispersing fog. However, one must be able to charge the droplets to a significant portion of the Rayleigh limit.

COMMENTS: In principle, the introduction of highly charged droplets should be capable of significantly modifying the development of warm clouds and dispersal of warm fogs.

REFERENCE: Latham, J., and M. H. Smith. "The Role of Electrical Forces in the Development and Dissipation of Clouds and Fog," NTIS Report No. AD-777-010, 17 pp., 1973.

OBJECTIVE: To study the role of electrical forces in the development and dissipation of clouds and fogs.

SIGNIFICANT PARAMETERS: Droplet fall depth, liquid water content, rainfall rate, radar reflectivity, drop concentration, size distribution, coalescence efficiency, relative humidity, and lapse rate.

TECHNIQUE DESCRIPTION: Theoretical calculations of the above parameters were made within a steady state rain shaft as a result of evaporation and interaction of the drops. The initial drop size distribution was characterized by the Marshall-Palmer equation. Three different situations were used: (1) evaporation without interaction, (2) interaction without evaporation, and (3) both interaction and evaporation.

FACTORS CONSIDERED IN NUMERICAL MODELS: Relative humidity gradient, rainfall rate, raindrop size distribution, initial slope of the raindrop size distribution, liquid water content, drop size, and relative humidity.

AUTHORS' CONCLUSIONS: It is concluded that, in principle, the introduction of highly charged drops into a fog can provide a highly efficient means of fog dispersal.

MERITS OF TECHNIQUE: Further studies regarding the advection of new fog at a rate faster than the dispersion mechanism can clear it and the possibility of using an optimum collector drop should be investigated.

COMMENTS: It appears that further field experiments are required before one can adequately assess this potentially attractive mechanism of dispersing warm fogs.

REFERENCE: Whitby, K. T. "Analysis of Electrogasdynamic Fog Dispersal," Department of Transportation, Federal Aviation Administration, FAA-ER-450-026, 51 pp., 1976.

OBJECTIVE: To analyze electrogasdynamic fog dispersal techniques.

SIGNIFICANT PARAMETERS: Electric charge carrier concentrations, particle mobility, droplet size, jet velocity, current density, distance from generator along jet axis, charge concentration, initial charge concentration, and generator flow rate.

TECHNIQUE DESCRIPTION: To analyze the papers previously published with regard to the electrogasdynamic fog dispersal concept.

AUTHOR'S CONCLUSIONS: The decay of charge in the electrogasdynamic generator's jet is by space charge with most of the charge leaving by 3 m from the generator. The electrogasdynamic generator may, therefore, be treated as a virtual point source of ions 2 to 3 m from the generator. The new models developed in this study indicate that it would take a great increase in generator output to ac...eve significant dispersal of fog.

MERITS OF TECHNIQUE: A possible recommendation is that a good, thorough study of a single electrogasdynamic generator be made under realistic conditions in order to determine such vital parameters as charge carry mobility, rate of charge carrier loss from the jet, and actual electrical fields.

REFERENCE: Ruhnke, L. H. "Warm Fog Modification by Seeding with Unipolar Ions," American Meteorological Society's Second National Conference of Weather Modification, Santa Barbara, California, pp. 385-388, 1970.

OBJECTIVE: To investigate the possibility of using electrostatic forces for modifying warm fog

SIGNIFICANT PARAMETERS: Decay rate, particle concentration, electrical mobility, space charge concentration, electric field, particle radius, and electric potential

TECHNIQUE DESCRIPTION: The continuity equation in steady state and Poisson's equation are used in this regard. A numerical integration of the equations was felt to be more convenient to describe conditions suitable for comparison with experimental results.

AUTHOR'S CONCLUSIONS: Evidence available from theory as well as experiments encourages experimentation in the free atmosphere under natural fog conditions of the electrostatic fog dispersal technique.

MERITS OF TECHNIQUE: The mobility of the charge carrier is extremely important in the overall efficacy of charged particle techniques for dispersal of warm fog. High mobilities as indicated by experiments would render the technique impractical unless particle generators of significantly larger size were developed and some way of eliminating particle precipitation near the generator itself could be developed.

COMMENTS: One needs to obtain valuable information such as mobility and charge density as a function of distance from the generator. After such information has been obtained, the equipment may be modified to create optimum conditions for dispersal of warm fog. Upon completion of characterization of the properties and capabilities of equipment, a field test should be attempted.

REFERENCE: Ruhnke, L. H. "Fog Droplet Sizes at the Panama Canal," NOAA Technical Report ERL-209-APCL-22, 17 pp., 1971.

OBJECTIVE: To measure fog droplet sizes at the Panama Canal

SIGNIFICANT PARAMETERS: Droplet diameter, nuclei concentrations, liquid water content, temperature, humidity, and cooling rate

TECHNIQUE DESCRIPTION: Fog droplet distributions and condensation nuclei measurements were taken at the Panama Canal. These data were collected using standard measurement techniques to supplement the micrometeorological measurements.

AUTHOR'S CONCLUSIONS: It was concluded that the high frequency of fog during certain times, the occurrence of fog under relatively persistent meteorological conditions, the low winds, and the moderate thickness of the fog layer all make the Panama Canal area an excellent ground for several fog modification concepts.

MERITS OF TECHNIQUE: Much experimental information concerning drop size distributions and cloud condensation nuclei are needed to create a data base for inclusion in available models and to facilitate decisions concerning possible fog dispersal techniques.

COMMENTS: The number of fog events monitored were not sufficient to establish adequate statistics.

REFERENCE: Whitby, K. T., B. Y. H. Liu, and C. M. Perterson. "Charging and Decay of Monodisperse Aerosols in the Presence of Unipolar Ion Sources," Journal of Colloid Science, Vol. 20, pp. 585-601, 1965.

OBJECTIVE: To investigate the charging and decay of monodisperse aerosols in the presence of unipolar ion sources

SIGNIFICANT PARAMETERS: Mobility, electric field, charge, number of concentrations, time, droplet radius, charge density, and charging time

TECHNIQUE DESCRIPTION: The physical behavior of uniform clouds of charged ions or particles, where the charge concentration is uniform throughout space, is not valid when ions are produced continuously in a space by concentrated ion sources--a case potentially of more technological importance.

AUTHORS' CONCLUSIONS: Experimental half-lives of the decaying aerosols were comparable to theory. The difference between theory and data for the free needle and commercial ionizer were due to the fact that experimental conditions did not approximate those assumed in theory.

MERITS OF TECHNIQUE: The overall technique of producing small low mobility particles appears to have good potential for warm fog dispersal.

COMMENTS: The work by the above authors deals solely with ions; however, the general concept most probably could be applied to the production of low mobility water droplets for projection into the atmosphere.

REFERENCE: Ruhnke, L. H. "Atmospheric Electric Cloud Modelling," Sonderdruck aus „Meterologische Rundschau," 25.Jahrgang, 2, Seite 38-41, 1972.

OBJECTIVE: To use numerical methods to calculate electric charges and electric fields in an atmosphere where data on convection and conductivity are available in parameter form.

SIGNIFICANT PARAMETERS: Air conductivity, space charge concentration, electric field, bipolar conductivity, permitivity, cloud droplet radius, cloud droplet concentration, liquid water content, and diffusion constant stant

TECHNIQUE DESCRIPTION: To analyze by theoretical methods the altitude profile of space charge concentrations in fair weather to show the influence of convection.

AUTHOR'S CONCLUSIONS: A significant change in the charge profile is produced by updrafts. It was also concluded that reasonable parameters of wind velocity of conductivity can not be found which produce electric fields at the ground sufficient to generate space charges by corona or to generate amounts of electricity found in thunderstorms.

MERITS OF TECHNIQUE: Studies of this type will enable one to more fully understand the sources and sinks of electricity by relating measured variables to physical and statistical laws.

COMMENTS: It is unfortunate that the complexity of the atmospheric electric state has limited theoretical studies of this kind.

REFERENCE: Jennings, S. G., and J. Latham. "The Charging of Water Drops Falling and Colliding in an Electric Field," Static Electricity, Paper 10, pp. 84-92, 1971.

OBJECTIVE: To study the charge transfer resulting from the collision and separation of water drops falling in an electric field

SIGNIFICANT PARAMETERS: Field strength, impact velocity, droplet radius, radius ratio, and angle

TECHNIQUE DESCRIPTION: Two uniformly sized droplet streams were ejected from hypodermic needles by modulating the flow of water through them and the two droplet streams were brought together between a pair of electrodes across which a potential difference existed.

AUTHORS' CONCLUSIONS: It is not difficult within clouds of fairly high precipitation and water content to separate charge at a rate of 1 coulomb per cubic meter per minute. However, the process envisioned in which a larger raindrop overtakes a smaller one, coalesces with it temporarily, swings around it, and separates from beneath it will act to dissipate existing electric fields.

MERITS OF TECHNIQUE: Experimental measurements of this kind will help to provide answers to the questions of how strong electric fields are generated and dissipated in clouds.

COMMENTS: The dissipative process mentioned above could provide a considerable obstacle to the generation of strong fields in rain clouds.

REFERENCE: Sartor, J. D., and C. E. Abbott. "Charge Transfer Between Uncharged Water Drops in Free Fall in an Electric Field," Journal of Geophysical Research, Vol. 73, No. 20, pp. 6415-6423, 1968.

OBJECTIVE: To investigate charge transfer between uncharged water drops in free fall in an electric field

SIGNIFICANT PARAMETERS: Droplet size, electric field, water conductivity, and separation distance

TECHNIQUE DESCRIPTION: To equal radius, water drops were allowed to fall between two vertical parallel plates which produced a uniform horizontal field and therefore acted as indirect sensors of the electric charge transferred between the drops. The drops approached each other in pairs with their line of centers parallel to the imposed field between the plates.

AUTHORS' CONCLUSIONS: The fact that drops in free fall can be charged via the spark transfer mode may be of considerable significance in the distribution of electricity in thunderstorms.

MERITS OF TECHNIQUE: The results of this study and others of similar nature are applicable to the remote sensing of highly electrified clouds.

COMMENTS: Sartor and Abbott suggest that more information is needed on the mechanical and hydrodynamic consequences of collisions between charged and uncharged particles of different sizes in the presence and absence of electric fields.

REFERENCE: Winn, W. P., G. W. Schwede, and C. B. Moore. "Measurement of Electric Fields in Thunderstorms," Journal of Geophysical Research, Vol. 79, No. 12, pp. 1761-1767, 1974.

OBJECTIVE: To determine the presence of intense electric fields inside active thunder clouds in central New Mexico

SIGNIFICANT PARAMETERS: Electric fields, current, voltage, altitude, and range

TECHNIQUE DESCRIPTION: To mount an instrument to measure electric fields perpendicular to a rocket's long axis, and to have the rocket penetrate the active thunder cloud

AUTHORS' CONCLUSIONS: The charge and regions of intense fields seem to be concentrated in relatively small volumes.

MERITS OF TECHNIQUE: Experimental measurements of electric field intensities should enhance present knowledge concerning intense precipitation and electrification techniques.

COMMENTS: Field studies of this type should be helpful in verifying present numerical models.

REFERENCE: Whitby, K. T. "Generator for Producing High Concentrations of Small Ions," The Review of Scientific Instruments, Vol. 32, No. 12, pp. 1351-1355, 1961.

OBJECTIVE: To develop a generator capable of producing high concentrations of small ions

SIGNIFICANT PARAMETERS: Decay rate, ion concentration, velocity, total ion output, flow rate, pressure, nozzle diameter, efficiency, and voltage gradient

TECHNIQUE DESCRIPTION: An arrangement of a needle and a sonic orifice was developed which is capable of converting the corona current into free ions with 100% efficiency. Positive and negative ion concentrations of 10^{11} ions per cubic centimeter in the sonic jet and total ion outputs of 10^{14} per second have been achieved.

AUTHOR'S CONCLUSIONS: The author concludes that the simplicity, low cost and high output of this type of ion generator will make it useful for studies of the behavior of ions in many scientifc areas.

MERITS OF TECHNIQUE: The technique shows potential for charging small water droplets for fog dispersal use.

COMMENTS: It might be possible to produce many small droplets with low mobility using the general type of conceptual design described.

REFERENCE: Vonnegut, B., C. B. Moore, G. E. Stout, D. W. Staggs, J. W. Bullock, and W. E. Bradley. "Artificial Modification of Atmospheric Space-Charge," Journal of Geophysical Research, Vol. 67, No. 3, pp. 1073-1083, 1962.

OBJECTIVE: To produce and release space charge of both positive and negative polarity into the atmosphere at a rate of about 1 milliampere.

SIGNIFICANT PARAMETERS: Electric potential gradient, wire diameter, wire length, and current charge density

TECHNIQUE DESCRIPTION: To stretch a horizontal wire approximately 14 km long and to make electrical measurements from an aircraft in order to assess the efficiency of using artificial charge as a tracer for micrometeorological studies.

AUTHORS' CONCLUSIONS: That space charge released from the ground is rapidly carried aloft by vertical currents of air during convective activity and even though the space charge produced at the ground is rapidly deleted by mixing, its effects are striking against the low natural background of space charge.

MERITS OF TECHNIQUE: The results indicate that cumulus clouds can be significantly and inexpensively modified by artificial means. However, stretching an electrical wire across much of the country does not appear to be a practical method for modifying the space charge.

COMMENTS: Experiments of this type indicate that the electric field may be significantly changed and that corona or ion particles may be used for micrometeorological tracers and studies of atmospheric circulation.

REFERENCE: List, R., and D. M. Whelpdale. "A Preliminary Investigation of Factors Affecting the Coalescence of Colliding Water Drops," Journal of the Atmospheric Sciences, Vol. 26, pp. 305-308, 1969.

OBJECTIVE: To investigate the factors affecting coalescence of colliding water drops

SIGNIFICANT PARAMETERS: Collision velocity, angle of impact, surface tension, and electric charge

TECHNIQUE DESCRIPTION: Droplets were produced using a hypodermic needle and the drops were placed in the path of rapidly rising droplets which were ejected by the bursting of air bubbles at an air-water interface.

AUTHORS' CONCLUSIONS: The coalescence efficiency should not always be set to 1.

MERITS OF TECHNIQUE: It is through this type of microphysical study that the answers to cloud electrification and lightning will probably eventually be answered.

COMMENTS: Information from microphysical studies of this type can be utilized in developing new ideas and models for future research in the area of microphysics and cloud electrification.

REFERENCE: Gourdine, M. C., T. K. Chiang, and A. Brown. "A Critical Analysis of the EGD Fog Dispersal Technique," The Cornell Engineer, Vol. 41, No. 2, pp. 14-35, 1975.

OBJECTIVE: To critically analyze an electrogasdynamic fog dispersal technique

SIGNIFICANT PARAMETERS: Electric field, electric potential, charged droplet size, mobility, wind speed, visibility, array dimensions, jet velocity, etc.

TECHNIQUE DESCRIPTION: Supersonic air jets located on the ground spray small charged water droplets into the atmosphere. Charge is transferred from the charged water droplets to the fog droplets and both the charged droplets and the fog droplets then drift earthward in the space charge induced electric field.

FACTORS CONSIDERED IN NUMERCIAL MODELS: Mobility, generator current output, air flow rate from the jet, precipitation time constant, current density, droplet size, electric fields, depth of the array in the direction of wind, number of generators, etc.

AUTHORS' CONCLUSIONS: The electrogasdynamic fog dispersal system offers significant advantages in installation costs, operating costs, and environmental impact over many other types of fog dispersal systems. They also conclude that there is a need for a test and demonstration at an operating airport.

MERITS OF TECHNIQUE: The electrogasdynamic technique shows potential for dispersal of warm fog.

COMMENTS: It is felt that further experiments to determine the important operating characteristics and significant physical parameters should be performed before a full-scale, demonstration-type experiment is attempted.

REFERENCE: Gourdine, M. C., G. B. Carvin, and A. Brown. "EGD Fog Dispersal System Scaling Laws," Unpublished paper and personal communication, 6 pp., 1978.

OBJECTIVE: To investigate electrogasdynamic fog dispersal system scaling laws

SIGNIFICANT PARAMETERS: Droplet mobility, electric field strength, mach number, temperature, jet speed, current density, penetration height of charged particle, droplet concentration, charge per droplet, etc.

TECHNIQUE DESCRIPTION: To derive scaling laws for an electrogasdynamic fog dispersal system which would include how the jets produce and disperse the charged water droplets; and then investigate how the charged water droplets attach themselves to fog droplets and finally how the fog droplets precipitate to the ground.

AUTHORS' CONCLUSIONS: To adequately test the electrogasdynamic fog dispersal system, one needs to simulate a one-dimensional airport model. This requires an array of at least 200 generators, such that the ratio of the width to the height of the treatment area is approximately 7 and end effects are negligible.

MERITS OF TECHNIQUE: The assumption that turbulent diffusion adequately mixes the charged particles so that the one-dimensional model can be assumed has not been extensively demonstrated.

COMMENTS: It would appear that some type of clearing effects would be evident using a smaller matrix. The information gathered from a smaller experiment could be used as the basis for further research using a larger matrix.

REFERENCE: Chiu, C. S. "Numerical Study of Cloud Electrification in an Axisymmetric, Time-Dependent Cloud Model," Journal of Geophysical Research, Vol. 83, No. C10, pp. 5025-5049, 1978.

OBJECTIVE: To use an axisymmetric time dependent numerical cloud model to study how an isolated convective cloud can be electrified when rain and cloud particles are allowed to be charged by the mechanisms of ion attachment and polarization

SIGNIFICANT PARAMETERS: Droplet radius, electric field density, ion mobility, ion concentration, total charge density, time, and liquid water content

TECHNIQUE DESCRIPTION: Numerical simulation of charge transports by electrical conduction, convection, turbulent mixing, and the particle terminal velocities are all simulated. The full dynamical-microphysical-electrical interactions are allowed in the simulation.

AUTHOR'S CONCLUSIONS: The application of a more sophisticated cloud model through the study of cloud electrification can lead to a much better and more realistic simulation of the electrical development in clouds and also gives a much better understanding of the function of the two charging mechanisms.

MERITS OF TECHNIQUE: The technique is beneficial in that the results can be used to help explain cloud electrification and precipitation mechanisms.

COMMENTS: Chiu has suggested that the study should be expanded to include hail and ice crystal growth processes and the model domain should be enlarged and the grid interval reduced. With these modifications the model could possible be used to test the many charge separation theories expounded today.

REFERENCE: Schlamp, R. J., S. N. Grover, H. R. Pruppacher, and A. E. Hamielec. "A Numerical Investigation of the Effect of Electric Charges and Vertical External Electric Fields on the Collision Efficiency of Cloud Drops," Journal of the Atmospheric Sciences, Vol. 33, No. 9, pp. 1747-1755, 1976.

OBJECTIVE: Numerically investigate the effect of electric charges and vertical external electric fields on the collision efficiency of cloud droplets and to determine the critical electric fields necessary to significantly affect the collision efficiency

SIGNIFICANT PARAMETERS: Drop size, electric charge, electric field strength, etc.

TECHNIQUE DESCRIPTION: To extend the numerical model of Schlamp, et al. (1976) to study charged and uncharged cloud drops in the presence or absence of a vertical electrical field where the large drop is negatively charged and the smaller drop is positively charged or the larger drop is negatively charged and the small drop below positively charged.

FACTORS CONSIDERED IN NUMERICAL MODELS: Reynolds number, drop size, charge on each drop, electric field strength, charge sign, relative velocity, trajectory, and the angle between the local vertical given by the direction of gravity.

AUTHORS' CONCLUSIONS: Electric fields and charges even of relatively modest values have a profound effect upon the collision efficiency. Electrostatic forces are responsible for determining the shape of the collision efficiency curves with the hydrodynamic forces being of secondary importance.

MERITS OF TECHNIQUE: The technique should help to answer some of the basic microphysical questions confronting cloud physicists today.

COMMENTS: A study of the collection efficiency including the coalescence efficiency, together with the collision efficiency, would be a very useful tool in investigating the effect of electric fields on droplet growth and precipitation mechanisms.

REFERENCE: Lakey, J. R. A., and W. Bostock. "Researches into Factors Affecting Electro-Precipitation," Transactions, Institution of Chemical Engineers, Vol. 33, pp. 252-263, 1955.

OBJECTIVE: To examine the discharge characteristics of small multi-wire plate precipitators

SIGNIFICANT PARAMETERS: Load resistance, component spacing, and diameter of the discharge wires

AUTHORS' CONCLUSIONS: There is no gain in discharge current by using a large number of wires spaced closely together. The type of discharge wire has a marked effect on the discharge current and general stability. The resistivity of the material to be precipitated greatly affects the efficiency of the process.

MERITS OF TECHNIQUE: The work covered in this paper includes a variety of practical problems connected with electro-precipitation; however, there are probably other fundamental problems which should be investigated.

COMMENTS: The authors suggest that among those areas for investigation which are of primary importance are migration velocity related to particle size for various discharge characteristics, the effect of gas composition, gas temperature on ionic mobility, and the measurement of electric field strengths under dust laden gas conditions.

REFERENCE: Melewicz, F., R. Conway, J. Hendrickson, S. Millington, C. Ball, J. Chen, M. Coggins, F. Coons, J. Link, W. Smith, R. Pierre, L. Goodwin, E. Van Vlaanderer, C. Workman, E. Mandel, and E. Hermic. "Ground-Based Warm Fog Dispersal Systems--Technique Selection and Feasibility Determination with Cost Estimates," Department of Transportation, Federal Aviation Administration, FAA-RD-75-126, 67 pp., 1975.

OBJECTIVE: To determine the feasibility and cost estimates of ground-based warm fog dispersal systems

SIGNIFICANT PARAMETERS: Visibility, airport minimums, benefit to cost ratios, costs, and cross wind thermal patterns

TECHNIQUE DESCRIPTION: The potential of numerous techniques and systems for dispersal of warm fog were analyzed. The majority of the effort was concentrated in the area of thermal systems with cost estimates and feasibility of these systems emphasized.

AUTHORS' CONCLUSIONS: Heat systems appear to be the only systems which show potential for dispersal of warm fog at airports. They further conclude that the warm fog dispersal techniques could be cost-effective in a number of major United States airports.

MERITS OF TECHNIQUE: It appears difficult to get an accurate cost estimate of such a system. The many variables involved in such an elaborate system would most probably prohibit an accurate cost estimate being made.

REFERENCE: Chiang, T. K., T. Wright, and R. Clark. "Field Evaluation of an Electrogasdynamic Fog Dispersal Concept," Department of Transportation, Federal Aviation Administration, FAA-RD-73-33, 69 pp., 1973.

OBJECTIVE: To evaluate an electrogasdynamic fog dispersal concept in the field

SIGNIFICANT PARAMETERS: Ionizer voltage, mach number, charge to mass ratio, drop radius, droplet charge, droplet mobility, visibility, wind speed, temperature, relative humidity, electric potential gradient, and charge density

TECHNIQUE DESCRIPTION: Sixteen charged particle generators were set up in the Panama Canal Zone for testing. Visibility improvements were measured during the tests.

AUTHORS' CONCLUSIONS: Results from the tests showed that while clearing trends were achieved during six out of eight tests, the magnitude and persistence of visibility improvement, as well as the time to achieve such improvement, varied widely from test to test.

MERITS OF TECHNIQUE: The merits of producing low mobility particles, which in turn transfer their charge to larger fog droplets for precipitation in an electric field is a concept which shows promise for dispersal of warm fog at airports.

COMMENTS: The characteristics of the generators, i.e., the mobility and the charge density as a function of distance from the generator should be adequately measured before full-scale field tests are conducted.

REFERENCE: Tag, P. M. "A Numerical Simulation of Warm Fog Dissipation by Electrically Enhanced Coalescence, Part I: An Applied Electric Field," Journal of Applied Meteorology, Vol. 15, pp. 282-291, 1976.

OBJECTIVE: To numerically simulate warm fog dissipation by electrically enhanced coalescence using an applied electric field

SIGNIFICANT PARAMETERS: Droplet size, charge, collision efficiency, visibility, and liquid water content

TECHNIQUE DESCRIPTION: The prupose of the experiment is to determine the degree of visibility improvement one could expect in fogs as a result of one aspect of electrically enhanced coalescence--enhanced coalescence due to an external electric field on neutral drops. For this purpose, a numerical sikulation with a one-dimensional fog model which incorporates the process of collision coalescence was conducted.

AUTHOR'S CONCLUSIONS: It was determined that a noticeable improvement in visibility can be achieved only under extremely large field strengths and then only for certain fog spectra.

MERITS OF TECHNIQUE: The technique should, of course, include enhanced coalescence as a result of seeding with charged droplets, which would provide a more complete evaluation of electrically enhanced coalescence as a potential mechanism for clearing fog.

COMMENTS: The dependence of visibility on droplet spectra might yield some clues as to why some field experiemnts have been inconclusive to date.

REFERENCE: Tag, P. M. "A Numerical Simulation of Warm Fog Dissipation by Electrically Enhanced Coalescence, Part II: Charged Drop Seeding," Journal of Applied Meteorology, Vol. 16, pp. 683-696, 1977.

OBJECTIVE: To numerically simulate warm fog dissipation by electrically enhanced coalescence-charged drop seeding

SIGNIFICANT PARAMETERS: Drop size, liquid water content, fog droplet size, visibility, electric field, and charge liquid water content

TECHNIQUE DESCRIPTION: To numerically simulate warm fog dissipation by electrically enhanced coalescence-charged drop seeding

AUTHOR'S CONCLUSIONS: Visibility improvement is closely linked to the size of the fog droplets and also increases with seeding rate. It also increases with seeding drop charge. This charge should be maximized as fully as possible.

MERITS OF TECHNIQUE: The numerical technique should be extended to include all possible charge to mass ratios and mobilities which could possibly be produced using a charge particle concept.

COMMENTS: The author suggests that with the information incorporated into the model that unless charging and seeding concentrations can be very greatly increased, charged drop seeding to enhance coalescence is probably not a viable technique.

REFERENCE: Sherman, P. M. "Measurements of Submicron Fog Particles Generated in a Nozzle," Journal of Aerosol Sciences, Vol. 6, pp. 57-65, 1975.

OBJECTIVE: To make measurements of submicron fog particles generated in a nozzle

SIGNIFICANT PARAMETERS: Particle size, nozzle velocity, stagnation temperature, stagnation pressure, and vapor pressure

TECHNIQUE DESCRIPTION: The primary purpose of the present measurements was to obtain new data; in particular, to determine the size of particles which form in a large supersonic nozzle.

AUTHOR'S CONCLUSIONS: Condensed particles will grow to a realtive large size in a large nozzle which yields a slow expansion. Initial partial pressure of vapor appears to be a good correlation factor for particle size for a range of total pressures. The number of particles condensed decreases or the growth rate increases and as the initial partial pressure of the vapor increases.

MERITS OF TECHNIQUE: The technique used is an optical one which measures the sizes of a total distribution of particles at one time.

COMMENTS: It would be very useful to be able to measure individual particle sizes. However, extremely strong light sources would be required.

REFERENCE: Abuaf, N., and C. Gutfinger. "Trajectories of Charged Solid Particles in an Air Jet Under the Influence of an Electrostatic Field," International Journal of Multiphase Flow, Vol. 1, pp. 513-523, 1974.

OBJECTIVE: To study the trajectories of solid particles in an air jet under the influence of an electrostatic field

SIGNIFICANT PARAMETERS: Particle size, jet velocity, electric field strength, charged fluid density, viscosity, dielectric constant of particles, and potential field

TECHNIQUE DESCRIPTION: Plastic particles are charged by a high voltage electrode inside a powder coating generator. The charged particles are then entrained by an air jet and directed towards the object to be coated which is electrically grounded.

AUTHORS' CONCLUSIONS: The influence of an electric field results in a more uniform flow of the particles when compared with the previously investigated similar case without electric fields. The presence of an electric field maintains the particles within the jet.

MERITS OF TECHNIQUE: The technique should be useful in helping to determine particle trajectories, collection efficiencies, particle movements and electric field gradients.

COMMENTS: The boundary conditions need to be changed before the results can be directly applied to a ground charged particle fog dispersal system.

REFERENCE: Chawla, T. C. "Droplet Size Resulting from Breakup of Liquid at Gas-Liquid Interfaces of Liquid-Submerged Subsonic and Sonic Gas Jets," International Journal of Multiphase Flow, Vol. 2, pp. 471-475, 1976.

OBJECTIVE: To study the droplet sizes resulting form the breakup of liquid at a gas liquid interface of liquid sumberged subsonic and sonic gas jets

SIGNIFICANT PARAMETERS: Droplet size, surface tension, mach number, viscosity, and wavelength

TECHNIQUE DESCRIPTION: The droplet size due to breakup of the liquid at the interfaces of subsonic and sonic gas jets submerged in a liquid were determined. The effect of mach number or compressibility of the gas stream on droplet size was investigated.

AUTHOR'S CONCLUSIONS: Good correlation between the experimental results obtained and the theory is possible.

MERITS OF TECHNIQUE: The technique has merit for a number of fields in chemical engineering and in the production of droplets using sonic nozzles.

COMMENTS: The analysis could probably be changed to incorporate a supersaturated condensation-type investigation for studies of charged particle fog dispersal concepts.

REFERENCE: Chapman, S. "The Magnitude of Corona Point Discharge Current," Journal of the Atmospheric Sciences, Vol. 34, pp. 1801-1809, 1977.

OBJECTIVE: To investigate and calculate the magnitude of corona point discharge

SIGNIFICANT PARAMETERS: Corona point discharge, current, potential wind speed, height, ambient electric field, ion speed, and polarity

TECHNIQUE DESCRIPTION: The article represents a first step beyond a dimensional argument to develop a quantitative theory for the magnitude of corona point discharge for a reasonably isolated point either in wind or in an ambient field.

AUTHOR'S CONCLUSIONS: The magnitude of corona point discharge is affected by point potential, by ion speed determined as a vector sum of motion in the field and in the wind, by nearby electrodes which have electrical images and which also eliminate space charges that would exist if the electrodes were further away, and, most importantly, by the conditions of the field, space charge, and wind immediately around the point.

MERITS OF TECHNIQUE: Experiments of this type should give an indication of the magnitude and duration of corona discharges from natural and pointed structures which, in turn, should give an indication of whether a propagating flame will result from corona discharges due to the electric fields set up by a charged particle fog dispersal technique.

COMMENTS: It does not appear at first glance that corona discharges will have sufficient current and be of sufficient duration to ignite fuel in the refueling area. However, much more information and study needs to be accomplished before a definite statement can be made in this regard.

REFERENCE: Vonnegut, B., and C. B. Moore. "Effect of Atmospheric Space-Charge on Initial Electrification of Cumulus Clouds," Journal of Geophysical Research, Vol. 67, No. 10, pp. 3909-3922, 1962.

OBJECTIVE: To determine the effect of atmospheric space-charge on initial electrification of cumulus clouds

SIGNIFICANT PARAMETERS: Electric potential, space-charge, droplet size, updraft velocity, liquid water content, conductivity, and potential gradient

TECHNIQUE DESCRIPTION: Artificially produced space-charge was released into the atmosphere and onto the ground during convections. Measurements indicated that clouds which form in the electrically modified region exhibited significantly larger potential gradient perturbations than otherwise similar clouds forming nearby.

AUTHORS' CONCLUSIONS: It should be concluded that space-charge of natural origin in the lower atmosphere can similarly determine the intensity and polarity of electrification and convective clouds.

MERITS OF TECHNIQUE: Investigations of this type should be continued to increase our knowledge of electrification in clouds and fogs.

REFERENCE: Verma, T. S., and N. C. Varshneya. "Point-Discharge Currents at Low Winds," Journal of Atmospheric and Terrestrial Physics, Vol. 36, pp. 351-357, 1974.

OBJECTIVE: To experimentally study point discharge currents at low wind velocities using a sharp metal point

SIGNIFICANT PARAMETERS: Wind velocity, electric field, threshold potential, potential difference between the point and surroundings, point-discharge current, point geometry, ion trajectory, and mobility of the ions

TECHNIQUE DESCRIPTION: A sharp metal point was kept at a high potential and mounted in a wind tunnel and the resulting point-discharge current measured at different wind speeds.

AUTHORS' CONCLUSIONS: There is a linear dependence of point-discharge current on high wind speeds. At low wind speeds, however, there is a deviation from the linear dependence, the current increases as the wind speed decreases.

MERITS OF TECHNIQUE: In general, experimental laboratory results cannot be completely adopted to the atmospheric phenomena where the conditions are not as uniform.

COMMENTS: The results are, however, significant and do indicate a possible point-discharge current wind speed correlation existing in the natural atmosphere.

REFERENCE: Woessner, R. H., and R. Gunn. "Measurements Related to the Fundamental Processes of Aerosol Electrification," Journal of Colloid Science, Vol. 11, pp. 69-76, 1956.

OBJECTIVE: To illuminate the fundamental processes responsible for the electrification of aerosols

SIGNIFICANT PARAMETERS: Droplet size, particle size, conductivity of the environment, charge, and temperature

TECHNIQUE DESCRIPTION: A number of measurements are made to compare the initial distribution of charges carried by various aerosols with their final equilibrium state.

AUTHORS' CONCLUSIONS: The aging of aerosols depends critically upon the intensity of the gaseous ionization. The initial electrification of an aerosol by mechanical means that separate charge by frictional contact is not questioned, but the continued maintenance of this electrification does not seem to be consistent with the experimental results.

MERITS OF TECHNIQUE: Aerosols of initially neutral particles or very highly charged particles establish substantially the same type of equilibrium distribution in times that are roughly inversely proportional to the intensity of ionization or the electric conductivity of the air. This establishes that the fundamental charging process is ionic in nature.

COMMENTS: The authors suggest that surface active forces of oriented molecules play a minor role in establishing the equilibrium. Accordingly, it can be concluded that theoretical and experimental analyses have shown that the observed charge distribution appearing on typical stable aerosols is fundamentally due to ionic diffusion.

REFERENCE: Pinnick, R. G., D. L. Hoihjelle, G. Fernandez, E. B. Stenmark, J. D. Lindberg, G. B. Hoidale, and S. G. Jennings. "Vertical Structure in Atmospheric Fog and Haze and Its Effects on Visible and Infrared Extinction," Journal of the Atmospheric Sciences, Vol. 35, pp. 2020-2032, 1978.

OBJECTIVE: To measure the vertical structure of the size distribution and number concentration of particulates in atmospheric fog and haze and to determine its effects on visible and infrared extinction

SIGNIFICANT PARAMETERS: Droplet size, liquid water content, wavelength, extinction coefficient, and density

TECHNIQUE DESCRIPTION: Vertical structure and size distribution and number concentration of particles in atmospheric fog and haze were measured using a balloon-borne light scattering aerosol counter for a period spanning parts of eight days.

AUTHORS' CONCLUSIONS: Extinction is found to be approximately proportional to $1/\lambda$ for haze conditions but nearly independent of wavelength for fog.

MERITS OF TECHNIQUE: There exists a size distribution independent linear relationship between particle extinction coefficient and liquid water content at 10 microns.

COMMENTS: The autors suggest that the approximate relationships found between extinction (from visible through 4 microm wavelenghts and liquid water content are probably attributed to a common form of fog and haze size distributions that were measured.

REFERENCE: Jiusto, J. E. "Laboratory Evaluation of an Electrogasdynamic Fog Dispersal Concept," Department of Transportation, Federal Aviation Administration, FAA-RD-72-99, 26 pp., 1972.

OBJECTIVE: To make a laboratory evaluation of an electrogasdynamic fog dispersal concept

SIGNIFICANT PARAMETERS: Ionizer voltage, air pressure, droplet generator dimensions, air flow rate, water consumption, velocity, droplet radius, droplet charge, electric field, and mobility

TECHNIQUE DESCRIPTION: The charged driplet generator was placed in the fog chamber and the visibility monitored as a function of time. Several different size generators with varying capabilities were used.

AUTHOR'S CONCLUSIONS: Due to numerous spray gun changes during the experiment and the uncertanity over the principle mechanism involved capability for clearing fog in the field was not possible.

MERITS OF TECHNIQUE: The laboratory tests do indicate that further concept study and approproiate field tests in actual fog are warranted.

COMMENTS: The technique shows potential for operational use at airports for dissipation of warm fog; however, the basic mechanisms involved and the basic characteristic of the droplet generators must be determined in order that effective further studies can be carried out.

REFERENCE: Schacher, G. F., and W. Reese. "Experiments Supporting a Program of Warm Fog Dispersal by Electrical Charge Injection," NTIS Report No. AD-775-911, 38 pp., 1974.

OBJECTIVE: To conduct experiments to support a program of warm fog dispersal by electrical charge injection.

SIGNIFICANT PARAMETERS: Charge droplet size, soap film bubble size, charge to mass ratio, electric field, and surface tension

TECHNIQUE DESCRIPTION: Experiments were made to determine the charge transfer to water sprays which showed that contact charging mechanisms were as much at 10^6 times as effective as induction charging mechanisms.

AUTHORS' CONCLUSIONS: Tests indicated that corona injection into the atmosphere produced considerable charge on windborne particles.

MERITS OF TECHNIQUE: The techniques of direct charging or contact charging are much more efficient thatn induction charging mechanisms.

COMMENTS: It is most likely that any fog dispersal system will require that contact charging mechanisms be used as opposed to induction charging mechanisms.

REFERENCE: Vonnegut, B., D. C. Blanchard, and R. A. Cudney. "Structure and Modification of Clouds and Fogs," AFCRL-71-0041, 207 pp., 1970.

OBJECTIVE: To investigate the structure and modification of clouds and fogs

SIGNIFICANT PARAMETERS: Raindrop and cloud dynamics, ice nucleation and freezing phenomena, instrumentation and atmospheric electrical phenomena

TECHNIQUE DESCRIPTION: Many different techniques were used by a number of different authors.

AUTHORS' CONCLUSIONS: It will not be possible to include each of the authors; conclusions for the entire reference cited above. A good many of the articles included in this publication, however, will be individually considered in this literature survey.

COMMENTS: The format of putting together in one document several articles with a general underlying theme, such as the structure and modification of clouds and fogs, greatly facilitates literature searches and enhances the possibility of the reader understanding the overall emphasis of the subjects involved.

REFERENCE: "Potential Economic Benefits of Fog Dispersal in the Terminal Area, Part I: Estimating Procedure," Department of Transportation, Federal Aviation Administration, FAA-RD-71-44-I, AD-735-132 (NTIS), 213 pp., 1971.

OBJECTIVE: To investigate the possible economic benefits of fog dispersal in the terminal area

SIGNIFICANT PARAMETERS: Fog conditions, temperature, weather category, and location of airport.

TECHNIQUE DESCRIPTION: Information was gathered to provide estimates of the cost of disruptions, delays, diversions and cancellations of aircraft landings associated with Catergory II and III weather definitions with an emphasis on fog situations. Major air carrier airports in the United States were considered.

AUTHORS' CONCLUSIONS: Any attempt to summarize the findings for the individual airports as general conclusions is complicated by the considerable inter-airport variation in the incidence pattern of the weather situations.

MERITS OF TECHNIQUE: In order to adequately assess the benefits one would derive from a fog dispersal system one needs to assess the cost due to delays and diversions, etc., at the major airports in the U.S.

COMMENTS: It appears that a number of fog dispersal techniques are economically feasible.

REFERENCE: Marut, J. K. "Statistical Analysis of Meteorological Parameters During Fog at 45 U.S. Airports," Department of Transportation, Federal Aviation Administration, FAA-RD-72-39, 263 pp., 1972.

OBJECTIVE: Put together a statistical analysis of meteorological parameters during fog at 45 United States airports.

SIGNIFICANT PARAMETERS: Wind speed, wind direction, visibility, temperature, and cumulative totals of the parameters.

TECHNIQUE DESCRIPTION: To analyze pertinent climatolobical data at 45 United States airports for a ten-year period between 1956 and 1965

AUTHOR'S CONCLUSIONS: Wind data is of most important particularly for locating ground-based fog dispersal systems. Gathering information is essential in order that an objective judgment for the possible design of systems to disperse and/or prevent fog at airports can be made.

COMMENTS: The threshold speed for most wind measuring instruments is approximately two knots depending on the mechanical condition of the instrument. As a consequence, the data will be skewed toward a greater percentage of calm conditions that actually exist during fogs.

REFERENCE: Wagner, P. B., and J. W. Telford. "Dissipation of Marine Stratus," Conference on Cloud Physics and Atmospheric Electricity--Preprints, pp. 225-228, 1978.

OBJECTIVE: To measure extensively the environment in stratus clouds off the Northern California coast, especially during their formation and dissipation.

SIGNIFICANT PARAMETERS: Wind, temperature, pressure, liquid water content, infrared radiation, field strength, and conductivity.

TECHNIQUE DESCRIPTION: To operate an aircraft in and near stratus clouds and to measure the above discussed parameters.

AUTHORS' CONCLUSIONS: The mechanical energy released when parcels of cloud evaporate and are cooled can help overcome the high stability which is present at the inversion.

MERITS OF TECHNIQUE: Observational techniques of this kind will help to reveal the dynamics of fog formation and dissipation.

COMMENTS: The authors state that due to the complexity of fog formation and dissipation, it is at times difficult to interpret one's results from the limited amount of data usually obtained in an experimental endeavor of this type. Sufficient statistics need to be built up in order to objectively assess the mechanisms for dissipation and formation.

REFERENCE: Hudson, J. G. "Fog Microphysical Measurements on the West Coast," Conference on Cloud Physics and Atmospheric Electricity--Preprints, pp. 198-205, 1978.

OBJECTIVE: To see what, if any, effect variations in the concentration of condensation nuclei have on fog microstructure.

SIGNIFICANT PARAMETERS: Nuclei concentration, liquid water content, droplet size, supersaturation, and visibility

TECHNIQUE DESCRIPTION: Cloud condensation nuclei were measured at low values of supersaturation by using an isothermal haze chamber. Field measurements of fog concentration were made at three coastal locations. Two continuous flow diffusion chambers and one isothermal haze chamber were used.

AUTHOR'S CONCLUSIONS: Fog visibility can be affected by variations in nuclei concentrations.

MERITS OF TECHNIQUE: Experimental measurements of fog characteristics using this type of equipment will yield a greater knowledge about fog formation and the effects of visibility due to nuclei concentrations.

COMMENTS: The fog condensation nuclei concentrations will affect the rate of natural droplet fallout; in turn, this will affect the electrostatic precipitation of charged particles.

REFERENCE: Schlamp, R. J., S. N. Grover, H. R. Pruppacher, and A. E. Hamielec. "Further Numerical Studies on the Effect of Electric Charges and Electric Fields on the Collision Efficiency of Cloud Drops," Conference of Cloud Physics and Atmospheric Electricity--Preprints, pp. 68-71, 1978.

OBJECTIVE: To investigate the complicated behavior of electrically charged drops colliding in the presence of external electric fields.

TECHNIQUE DESCRIPTION: New computations using a theoretical model and computational scheme were used to determine the complex relationships between the various hydrodynamic and electrostatic forces involved in droplet coalescence.

FACTORS CONSIDERED IN NUMERICAL MODELS: The two following cases were considered in the present study: (1) the larger drop is negatively charged and initially above the smaller drop, which is positively charged, and (2) the larger drop is negatively charged and it is initially below the smaller drop, which is again positively charged.

AUTHORS' CONCLUSIONS: The authors conclude that the action of the external field on the charges carried by the drops results in a much decreased vertical component of the relative velocity of the two drops.

MERITS OF TECHNIQUE: Numerical calculations of this type should be very helpful in the determination of whether a charged particle fog dispersal technique can ultimately be used on a routine basis.

COMMENTS: There most probably exists a complex relationship between the various hydrodynamic and electrostatic forces in charged droplet coalescence processes. Further experimental and theoretical studies are needed before an objective judgment of all different physical combinations of charged drop size and electric field intensity and direction can be made.

REFERENCE: Phelps, C. T., and B. Vonnegut. "Charging of Droplets by Impulse Corona," Journal of Geophysical Research, Vol. 75, No. 24, pp. 4383-4490, 1970.

OBJECTIVE: To investigate the charging of droplets by impulse corona.

SIGNIFICANT PARAMETERS: Droplet radii, surface charged density, droplet acceleration, mobility, velocity, collision and coalescence efficiencies, droplet charge, droplet oscillation, and path length.

TECHNIQUE DESCRIPTION: Production of impulse corona of both polarities within a cloud of droplets atomized from a solution of glycerine and water were used.

AUTHORS' CONCLUSIONS: There are quite different charging mechanisms for the two corona polarities. With positive corona the droplet charging appears to result from direct interaction between the positive streamers and the droplets. In contrast to the situation with positive streamers, the negative corona serves only to supply the charge carriers in the overall charging process. This would indicate a possible link between the lightning discharge and subsequent rapid cloud droplet growth.

MERITS OF TECHNIQUE: Experiments of this type show great potential for eventually explaining the rain gush observed during severe storms.

COMMENTS: Whether the lightning causes the rain gust of the rain gush enhances charge separation are questions that need to be researched further.

REFERENCE: Markson, R., and R. Nelson. "Mountain-Peak Potential-Gradient Measurements and the Andes Glow," Weather, Vol. 25, No. 8, pp. 350-360, 1970.

OBJECTIVE: To study mountain peak potential gradients and the Andes glow.

SIGNIFICANT PARAMETERS: Electric field, strength, potential gradient, geological structure type, and electrode geometry.

AUTHORS' CONCLUSIONS: That several factors are magnifying the normal field strength near the mountains. These factors were thought to be fair weather electric field, geometrical packing, mountain and sharp rock, electrode effect, haze aurora, and extraterrestrial effects.

MERITS OF TECHNIQUE: This type of study should be helpful in determining the cause of St. Elmo's fire in the vicinity of aircraft while a charged particle fog dispersal system is in operation.

COMMENTS: Research studies of this type should help in answering the question of whether discharge which could start a propagating flame will occur in the terminal area due to the electric fields produced by a charged particle fog dispersal system.

REFERENCE: Kamra, A. K. "Effect of Electric Field on Charge Separation by the Falling Precipitation Mechanism in Thunderclouds," Journal of Atmospheric Sciences, Vol. 27, No. 8, pp. 1182-1185, 1970.

OBJECTIVE: To study the effect of electric fields on charge separation by the fall precipitation mechanism in thunderclouds.

SIGNIFICANT PARAMETERS: Electric field strength, precipitation rate, droplet size, charge, air conductivity, particle concentrations, velocity of smaller cloud particles, time for charge buildup.

TECHNIQUE DESCRIPTION: To use the growth rates of electric fields produced by induction charging mechanisms of charge generation in thunderclouds for calculations of precipitation rates.

AUTHOR'S CONCLUSIONS: In addition to point discharge, currents below the thundercloud and the conduction currents inside the thundercloud as leakage currents, that the electrical forces acting on precipitation in small size particles are important in determining the maximum electric field and the rate of charge separation of thunderclouds.

MERITS OF TECHNIQUE: The results can probably be used quantitatively for a better understanding of the generalized charge generation mechanism based on falling precipitation in thunderclouds.

COMMENTS: The author concludes that one must indeed take into account the role played by high electric field collisions of small and relatively larger particles in contributing to the net charge separation.

REFERENCE: Barreto, E. "Submicroscopic Aerosols from Electrically Stressed Water Surfaces," AFCRL-71-0041, pp. 94-126, 1970.

OBJECTIVE: To investigate the production of submicroscopic aerosols from electrically stressed water surfaces.

SIGNIFICANT PARAMETERS: Droplet size, electric field, mobility, polarity, and electrode gap.

TECHNIQUE DESCRIPTION: Both positive and negative drops of a few millimeters in diameter resting on metal electrodes are subjected to electric fields with subsequent production of charged aerosols.

AUTHOR'S CONCLUSIONS: A positive drop always exhibits an electrical instability prior to mechanical instability. Conversely, a negative drop exhibits first a mechanical instability and it is not clear at what stage breakdown is produced.

MERITS OF TECHNIQUE: This technique should help in understanding the charge transfer mechanics inherent in a charged particle fog dispersal system.

COMMENTS: The difference in behavior between positive and negative drops has not, as yet, been quantitatively explained. Further research must be pursued in this area.

REFERENCE: "Potential Economic Benefits of Fog Dispersal in the Terminal Area, Part II: Findings," Department of Transportation, Federal Aviation Administration, FAA-RD-71-44-II, AD-735-214 (NTIS), 340 pp., 1971.

OBJECTIVE: To develop an estimating procedure to assess the potential benefits of fog dispersal in the terminal area.

SIGNIFICANT PARAMETERS: Fog frequency, temperature, visibility, ceiling, aircraft landing system, and weather category.

TECHNIQUE DESCRIPTION: To search the available data on fog frequency and meteorological conditions in order to assess potential economic benefits of fog dispersal systems.

AUTHORS' CONCLUSIONS: The findings indicate the need for a technical and operational evaluation of the techniques and systems both with fog modification and electronic landing systems individually and in combination in terms of the specific airport environment to determine the optimum benefit cost configuration and to provide a measure of the degree of effectiveness of the different techniques.

COMMENTS: Information of this type will facilitate decisions such as which type of fog dispersal systems should be utilized at airports.

REFERENCE: Moschandreas, D. J. "Present Capabilities to Modify Warm Fog and Stratus," NTIS No. AD-776 261/0, 102 pp., 1974.

OBJECTIVE: To review the literature of warm fog dissipation.

TECHNIQUE DESCRIPTION: To conduct an in-depth review of the literature on warm fog dissipation; both theoretical and experimental projects were reviewed and comments were made on the reported claims.

AUTHOR'S CONCLUSIONS: The two most promising techniques are thermal dissipation of warm fog in stratus and the combination of seeding and helicopter techniques.

COMMENTS: Design of the least expensive and most effective warm fog dissipation techniques should be based on researched concepts and methods.

REFERENCE: Latham, J., and M. H. Smith. "The Role of Electrical Forces in the Development and Dissipation of Clouds and Fogs," NTIS Report No. AD-777-010, 17 pp., 1973.

OBJECTIVE: Study the role of electrical forces in the development and dissipation of clouds and fogs.

SIGNIFICANT PARAMETERS: Droplet radius, electric field, surface tension, droplet charge, droplet separation, and droplet distortion.

TECHNIQUE DESCRIPTION: A study of the parameters affecting coalescence with an emphasis on electric fields was carried out. The enhanced coalescence information and the effect of electric fields on collision and coalescence efficiencies were then used to determine the amount of fog or cloud development or dissipation which might occur.

AUTHORS' CONCLUSIONS: Modification of clouds and fogs by charged particles has the potential to influence particle growth over extended regions. Further, the utilization of electrical cloud seeding methods also offers considerable advantages both from ecological and operation viewpoints.

MERITS OF TECHNIQUE: The overall efficacy of the technique is still to be demonstrated. In order to test the ideas set forth, large fog chambers or field tests would probably be required.

COMMENTS: The problem of introducing large quantities of charge into the atmosphere should be evaluated.

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APPENDIX 2

DERIVATION OF EQUATION 3-10, PAGE 25

Consider the volume element of a jet shown in Figure A-1. A charge balance on the jet gives

$$\frac{d}{dx}\left(U' q n \pi r^2\right) = -\, 2\pi r q n z E_r \tag{A2-1}$$

From the relationship $\nabla \cdot E = qn/\varepsilon_o$, the value of E_r is found to be

$$E_r = qnr/2\varepsilon_o \tag{A2-2}$$

Recall from page 25 that $r = \alpha x + r_j$ where $\alpha = 0.085$. Substituting into Equation A2-1 and noting that $dr = \alpha dx$ we arrive at

$$\frac{d(U' q n r^2)}{(U' q n r^2)^2} = -\,\frac{z}{\alpha \varepsilon_o}\,\frac{dr}{(U' r)^2} \tag{A2-3}$$

Let $\eta = U' q n r^2$ and note the assumption that $U' = u_j r_j / r$. Equation A2-3 becomes

$$\frac{1}{\eta}\Bigg|_{\eta(x=0)}^{\eta(x)} = \frac{z}{\alpha \varepsilon_o}\,\frac{r}{(U_j r_j)^2}\Bigg|_{r(x=0)}^{r(x)} \tag{A2-4}$$

$$\frac{1}{\eta} - \frac{1}{\eta_o} = \frac{z}{\varepsilon_o}\,\frac{x}{(U_j r_j)^2} \tag{A2-5}$$

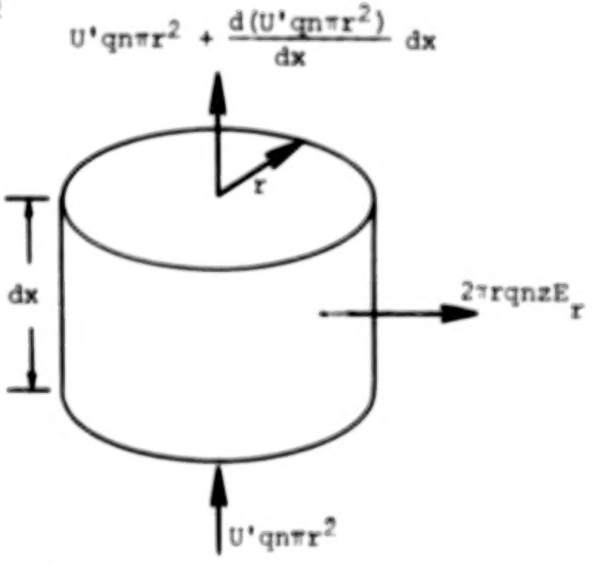

Figure A.1 Charge balance on the jet.

$$\frac{n_o}{n} = 1 + \frac{z}{\varepsilon_o} \frac{x}{(U_j r_j)^2} n_o \qquad \text{(A2-6)}$$

Substituting $n = U_j r_j qnr$ and $n_o = U_j r_j^2 (qn)_0$ into Equation A2-6 gives

$$\frac{r_j (qn)_0}{rqn} = 1 + \frac{z}{\varepsilon_o} \frac{x}{U_j} (qn)_0 \qquad \text{(A2-7)}$$

$$\frac{(qn)_0}{qn} = \frac{r}{r_j} \left(1 + \frac{2zE_r(0)}{U_j} \frac{x}{r_j} \right)$$

$$= 1 + \frac{2zE_0}{U_j} \left(\frac{x}{r_j} \right)^2 + \left(\alpha + \frac{2zE_r(0)}{U_j} \right) \frac{x}{r_j}$$

or finally

$$\frac{n}{n_o} = \frac{1}{1 + \frac{2zE_r(0)\alpha}{U_j} \left(\frac{x}{r_j} \right)^2 + \left(\alpha + \frac{2zE_r(0)}{U_j} \right) \frac{x}{r_j}}$$

Where Reference [23] has apparently neglected terms of order x/r_j to those of order $(x/r_j)^2$.

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16. ABSTRACT

The concept of using the charged particle technique to disperse warm fog at airports is investigated and compared with other techniques. The investigation indicates that the charged particle technique shows potential for warm fog dispersal but that many questions regarding important physical processes must be addressed both theoretically and through small-scale field testing prior to conducting major equipment development and large-scale field tests. For example, experimental verification of several significant parameters, such as particle mobility and charge density is needed.

Seeding and helicopter downwash techniques were also found to be effective for warm fog dispersal but presently are not believed to be viable techniques for routine airport operations. Thermal systems are effective and currently are used at a few overseas airports; however, they are expensive and pose potential environmental problems.

A state-of-the-art summary, literature survey, and charged particle concept analysis are described in detail in this report. The report illustrates that several of the previously listed techniques, through proper development, may have the potential to significantly reduce disruptions of aircraft operations due to warm fog. This could result in significant economical savings to the aviation community.

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